Integrated electrofuels and renewable energy systems

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INTEGRATED ELECTROFUELS AND RENEWABLE ENERGY SYSTEMS

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To cultural differences, to Danes and their optimism and to Croatians and their scepticism,

making me a sceptical optimist.

ABSTRACT

In order to enable an extensive penetration of fluctuating sources into an electric grid, it is necessary to rethink the design of the energy system and switch to a more coherent Smart Energy System approach. In the context of a 100% renewable energy system, transformation of the transport sector is the most challenging when the scarcity of biomass resources is accounted. Based on today's knowledge and expectations, it is unlikely that modal shift or electrification will completely remove the dependence on liquid or gaseous fuels in some modes of transport, such as heavy-duty trucks, shipping, and air travel. It is therefore necessary to rethink the production cycle of needed hydrocarbons and, at the same time, create flexibility that will enable an extensive penetration of fluctuating sources into the electric grid.

This dissertation presents a feasibility study, which investigates the different renewable fuel pathways that can meet the future transport needs in energy systems based on a high share of fluctuating renewable resources. The analysis is based on the reference scenario *100% Renewable Denmark in 2050*. The concept of merging a carbon source such as carbon dioxide emissions or biomass with hydrogen from steam electrolysis opens a way for new hydrocarbons. The aim of these fuels, which are defined in this study as electrofuels, is to convert electrical energy into chemical energy by means of electrolysers, thus connecting fluctuating renewable energy to the vast amount of fuel storage already available in today's energy systems. The aim of the study is to investigate different fuel pathways to create these electrofuels, review the individual stages of the production cycle, quantify the resources required to create each fuel, analyse their ability to integrate fluctuating renewable resources, assess the production costs of electrofuels, and to compare the socio-economy of these fuels with other fuel alternatives. The historical development of alternative fuel policies is investigated to address the awareness of transport alternatives and implications of existing legislation on the current electrofuel development are identified. The feasibility study concludes with a roadmap for the deployment of electrofuels in the future.

Three fuel pathways with two fuel outputs (methanol/dimethyl ether and methane) were developed and analysed in this dissertation: CO_2 electrofuels (CO_2 hydrogenation and co-electrolysis) and bioelectrofuels (biomass hydrogenation). The flexibility of electrofuels is based on not only their ability to integrate fluctuating electricity by storing it in fuel form, but also that they all finish with chemical synthesis, meaning that the resultant fuels can be adjusted to meet the requirements on the demand side. The implementation of electrofuels in the energy system has shown improvements in system flexibility; however, they also have a high investment cost due to the high installed capacities of offshore wind and electrolysers. The overall socio-economic results show that the electrofuels are comparable with other alternative options, and even when compared with second-generation biofuels they will have lower costs in the future. This

is due to the low resource demand for these fuels in comparison with biofuels. The analysis moreover showed that using different types of electrolysers does not have a significant influence on the total system costs; therefore, existing alkaline electrolyser technologies can be used instead of suggested solid oxide electrolyser cells. Out of the two analysed electrofuel outputs, production of methanol/dimethyl ether is more efficient than that of methane, and associated costs for altering existing infrastructure are lower.

The results talk in favour of liquid pathways; however, if the breakthrough in the development of heavy-duty gas vehicles will make them more efficient than vehicles running on liquid fuels, then the results would favour gaseous output. It is important to note that the specific fuel mix that will be deployed in the future should not be the key focus, as electrofuel pathways share all critical technologies, so the development of these technologies should be prioritised before the final fuel is pursued. This research has enhanced the understanding of electrofuels as part of the Smart Energy Systems, with the results indicating that they can be a feasible element in the future energy systems with today's assumed technological development.

DANSK RESUMÉ

Hvis vi i langt højere grad skal anvende fluktuerende vedvarende energikilder som vindkraft og solceller, skal de indgå i et mere sammenhængende og intelligent energisystem end det, vi kender i dag. En af de største udfordringer ved omstillingen til et 100 % vedvarende energisystem er olieforbruget i transportsektoren - især set i lyset af, at biomasseressourcerne er begrænsede. Selvom man elektrificerer persontransporten og skifter til øget togtransport, er det usandsynligt, at den tunge transport, der varetages af lastbiler, skibe og fly, kan elektrificeres via batterier. Derfor er der et behov for at forske i flydende eller gasformige brændsler, som kan fremstilles syntetisk og på en måde, der optimerer anvendelsen af de fluktuerende vedvarende energikilder.

Denne afhandling præsenterer et feasibility-studie med fokus på de samfundsøkonomiske og ressourcemæssige konsekvenser ved forskellige produktioner af brændsler baseret på fluktuerende vedvarende energikilder. Analysen tager udgangspunkt i et referencescenarie med 100 % vedvarende energi i Danmark i år 2050 inklusiv transport. Ved at forbinde en kulstofkilde, såsom kuldioxid fra atmosfæren, punktkilder eller røggasser fra forbrænding af biomasse, med brint fra elektrolyse, kan man fremstille nye kulbrinter. Målet med disse brændsler, som i denne afhandling kaldes elektrobrændsler, er at konvertere elektrisk energi til kemisk energi ved hjælp af elektrolyse. Dermed forbindes den fluktuerende vedvarende energi med store kapaciteter i brændselslagre, som allerede eksisterer i det nuværende energisystemer. Formålet med dette studie er at undersøge de forskellige mulige metoder til produktion af elektrobrændsler. Afhandlingen skal vurdere de individuelle stadier i produktionscyklussen, kvantificere de nødvendige ressourcer til produktion af forskellige brændsler, analysere deres evne til at bidrage til integrationen af fluktuerende, vedvarende energikilder, vurdere produktionsomkostningerne ved elektrobrændsler og endelig sammenligne de samfundsøkonomiske omkostninger af disse med andre alternative transportbrændsler. Derudover gennemgår afhandlingen politikker for alternative transportbrændsler i et historisk perspektiv for at afdække bevidstheden om eksistensen af elektrobrænsler, samt for at knytte den eksisterende lovgivning til udviklingen for elektrobrændsler. Afhandlingen rundes af med en handlingsplan for udviklingen af elektrobrændsler i fremtiden.

Tre produktionsformer med to resulterende brændselstyper (metanol/dimetylæter og metan) er blevet undersøgt og analyseret: CO_2-elektrobrændsler (CO_2-hydrogenering og sam-elektrolyse) og bio-elektrobrændsler (biomasse-hydrogenering). Fleksibiliteten i elektrobrændsler er ikke kun baseret på deres evne til at lagre el som brændsel og dermed bidrage til integrationen af den fluktuerende el-produktion. Den kemiske syntese, som processen for alle elektrobrændsler afsluttes med, betyder desuden, at det resulterende brændsel kan tilpasses specifikt til kravene på forbrugssiden. Implementeringen af elektrobrændsler i energisystemet har vist sig at forbedre systemfleksibiliteten, men

omkostningerne ved disse systemer er også høje grundet store behov for havvindmøller og elektrolyseanlæg. Det overordnede samfundsøkonomiske resultat viser imidlertid, at elektrobrændsler er sammenlignelige med andre alternative løsninger og har lavere omkostninger end andengenerationsbiobrændsler i fremtiden. Dette skyldes, at elektrobrændsler har et lavt biomasseforbrug sammenlignet med biobrændsler. Analysen viser også, at typen af elektrolyseanlæg ikke påvirker resultaterne markant, og at eksisterende alkaliske elektrolyseanlæg derfor kan bruges i stedet for de foreslåede fastoxid-elektrolyseceller (SOEC). Analysen af de tre elektrobrændsler viser, at produktionen af metanol og dimetylæter (DME) er mere effektiv end metan, og de tilhørende omkostninger til ny infrastruktur er lavere grundet mere effektive køretøjer. Resultaterne taler til fordel for systemer baseret på flydende brændsel, men hvis et gennembrud i udviklingen af gaskøretøjer til tung transport skulle gøre disse mere effektive, ville resultatet kunne ændre sig til fordel for gasformige brændsler. Det er vigtigt at notere sig, at det ikke er den specifikke sammensætning af brændsler, der er det vigtigste, da alle kritiske teknologipunkter er fælles for alle elektrobrændsler. Derfor bør udviklingen af teknologier prioriteres, inden man går videre med specifikke brændsler. Forskningen i denne afhandling har udbygget forståelsen af elektrobrændsler som en vigtig del af intelligente energisystemer og løsningen af problemet vedrørende særligt den tunge transport. Resultaterne viser, at elektrobrændsler udgør et muligt element i det fremtidige energisystem baseret på den forventede teknologiske udvikling.

LIST OF APPENDED PAPERS

This dissertation is based on five journal papers that are included in the Appendices:

I. Ridjan I, Mathiesen BV, Connolly D. *Terminology used for renewable liquid and gaseous fuels produced by conversion of electricity: a review*. [Accepted for publication in Journal of Cleaner Production]

II. Mathiesen BV, Lund H, Connolly D, Wenzel H, Østergaard PA, Möller B, Nielsen S, Ridjan I, Karnøe P, Sperling K, Hvelplund F. *Smart Energy Systems for coherent 100% renewable energy and transport solutions*. Applied Energy, Volume 145, 1 May 2015, Pages 139-154, ISSN 0306-2619, http://dx.doi.org/10.1016/j.apenergy.2015.01.075.

III. Ridjan I, Mathiesen BV, Connolly D. *Synthetic fuel production costs by means of solid oxide electrolysis cells*. Energy, Volume 76, 1 November 2014, Pages 104-113, ISSN 0360-5442, http://dx.doi.org/10.1016/j.energy.2014.04.002.

IV. Connolly D, Mathiesen BV, Ridjan I. *A comparison between renewable transport fuels that can supplement or replace biofuels in a 100% renewable energy system*. Energy, Volume 73, 14 August 2014, Pages 110-125, ISSN 0360-5442, http://dx.doi.org/10.1016/j.energy.2014.05.104.

V. Ridjan I, Mathiesen BV, Connolly D, Duić N. *The feasibility of synthetic fuels in renewable energy systems*. Energy, Volume 57, 1 August 2013, Pages 76-84, ISSN 0360-5442, http://dx.doi.org/10.1016/j.energy.2013.01.046.

"This thesis has been submitted for assessment in partial fulfilment of the PhD degree. The thesis is based on the submitted or published scientific papers which are listed above. Parts of the papers are used directly or indirectly in the extended summary of the thesis. As part of the assessment, co-author statements have been made available to the assessment committee and are also available at the Faculty. The thesis is not in its present form acceptable for open publication but only in limited and closed circulation as copyright may not be ensured."

Other relevant publications, which have not been included in the Appendices but are publicly available:

i. Mathiesen BV, Ridjan I, Connolly D, Nielsen MP, Vang Hendriksen P, Bjerg Mogensen M *et al. Technology data for high temperature solid oxide electrolyser cells, alkali and PEM electrolysers*. Department of Development and Planning, Aalborg University, 2013, 16 pages.

ii. Ridjan I, Mathiesen BV, Connolly D. *A review of biomass gasification technologies in Denmark and Sweden*. Copenhagen, Denmark: Department of Development and Planning, Aalborg University; 2013, 33 pages.

iii. Ridjan I, Mathiesen BV, Connolly D. *SOEC pathways for the production of synthetic fuels - The transport case*. Department of Development and Planning, Aalborg University, 2013, 47 pages.

CONTENTS

LIST OF ABBREVIATIONS

BIOFRAC	Biofuels Research Advisory Council
BTE	Biomass-to-electrofuels
BTL	Biomass-to-liquid
CARS21	Competitive Automotive Regulatory System for the 21st century
CEEP	Critical excess electricity production
CCR	Carbon capture and recycling
CCS	Carbon capture and storage
CDU	Carbon dioxide utilisation
CHP	Combined heat and power
CNG	Compressed natural gas
CoR	Committee of the Regions
CTE	Coal-to-electrofuels
CTL	Coal-to-liquid
DG	Directorates-General
DME	Dimethyl ether
EBTP	European Biofuels Technology Platform
EC	European Commission
ECCP	European Climate Change Programme
EESC	European Economic and Social Committee
ETE	Emission(CO_2)-to-electrofuels
EU	European Union
EV	Electric vehicle
FCEV	Fuel cell electric vehicle
FFV	Flexi-fuel vehicles
F–T	Fischer–Tropsch
FQD	Fuel Quality Directive
GTL	Gas-to-liquid
GHG	Greenhouse gas
ICE	Internal combustion engine
IEEP	Institute for European Environmental Policy
IFPRI	International Food Policy and Research Institute
ILUC	Indirect land use changes
LCA	Life cycle analysis
LPG	Liquefied petroleum gas
NGOs	Non-governmental organisations
PEM	Polymer exchange membrane
PTL	Power-to-liquid
RED	Renewable Energy Directive

RGWS	Reversed gas water shift
R&D	Research and development
SES	Smart Energy System
SNG	Synthetic natural gas
SOEC	Solid oxide electrolyser cell
xTE	*coal-, biomass-, emission(CO_2)*-to-electrofuel
xTL	*coal-, gas-, biomass*-to-liquid
WTO	World Trade Organisation

PREFACE

My PhD journey started unofficially back in 2011 when I received an opportunity to do a 3-month internship at the Sustainable Energy Planning Research Group at Aalborg University in Copenhagen. This internship developed into a fruitful experience that consequently led to my Master thesis—a Master thesis that could be seen as a preliminary assessment of electrofuels in renewable energy systems. Three months after my graduation in Croatia, I then received a call from my internship host and co-supervisor Brian Vad Mathiesen with an offer to return to the research group and start working as a research assistant. Saying that I was excited about this prospect would be an understatement. Being offered a chance to return to the country, the colleagues, and a research area that I had grown so fond of was close to a dream come true. One thing led to another, and eventually I applied for a PhD position in the research group with Brian as my supervisor and within the topic of transport as part of 100% renewable energy systems. Therefore, I need to send my gratitude to a number of people who have made my research possible.

I would like to give special thanks to my supervisor, Brian, for making it all happen, for letting me fight my old demons, for teaching me how to be more independent, for introducing me to an interesting world of electrofuels, and for your continuous support. My sincere thanks go out to David Connolly for keeping up with my bad English, and patiently correcting it. I now see how far I have developed since my first few drafts, but I will never forget your time invested in helping me out; thank you for much constructive feedback and great advice. As our group grew over time, over two campuses, I would like to thank all of you for such a great working environment and for fruitful discussions. I am very lucky to be part of "energy guys" because being a lady never made me different from others.

I would like to thank all of my colleagues in the Department of Development and Planning who always made sure that I felt like I was where I belonged, for many conversations in both English and Danish, and for great cakes on Thursdays. Many thanks go to my colleagues at ITS for engaging me in different activities and exchanging data during my research stay at UC Davis, California. My visit would not have been possible without receiving financial support from the Danish Ministry of Higher Education & Science, which granted me an EliteForsk travel scholarship that enabled my stay in California and visits to Stanford and MIT. I am very grateful and honoured for having received this opportunity.

Special thanks go to my family, for all of the love and care, for supporting me in pursuing my academic career, for not once complaining that I call Denmark "home" these days, and for never doubting that I could achieve big things, even when I doubted it myself.

Of course, to my Laurits, for keeping up with this temperamental Balkan lady of yours, and for your love and support, continuous encouragement, and cheerfulness throughout this venture—you rock my world.

To my dear friends, the new ones and the old ones, irrespective of the distance between us.

It is early to do so, and I am too young to say this, but looking back, I believe that accepting the first and second offers to work with SEP were the best decisions I have ever made! Despite that every last penny has been squeezed out of me as a foreign student having living expenses in Copenhagen, I feel that I have somewhat managed to transform my life from my first visit to AAU to something great. I can proudly say: I feel a bit more Danish now and I have never been happier.

I hope you will find my work valuable and enjoy reading it.

1 INTRODUCTION

1.1 SHIFTING FROM FOSSIL TO RENEWABLE FUELS

Changing an energy system is a very challenging task that is encircled with many uncertainties. However, the energy challenges are clear: there is a need to find a solution to environmental issues caused by currently used fossil fuels, the lack of security of supply, and to achieve positive socio-economic development. These challenges are imbedded in the search for alternative solutions for the existing energy systems worldwide that are based on fossil fuels. This shift from fossil fuels to renewable energy sources and fuels is necessary to happen in the next decades, as the resources are limited and unevenly distributed; more importantly, the greenhouse gas emissions need to be reduced. The uncertainties on how to perform this transition are present due to many different notions of how to solve this problem, many actors involved who have their own agendas, and renewable alternatives that are still at the development level and have to fit in the current energy system. Even at the current stage, where some sectors have been successfully integrating renewable energy sources as a solution to energy challenges encountered, the transport sector has been lagging behind. Transport is responsible for 19.7% of the total emissions from all sectors in the European Union [1], and is the only sector that experienced a constant rise of emissions from 1990 to 2007, when the emissions slowly started to decrease (see Figure 1).

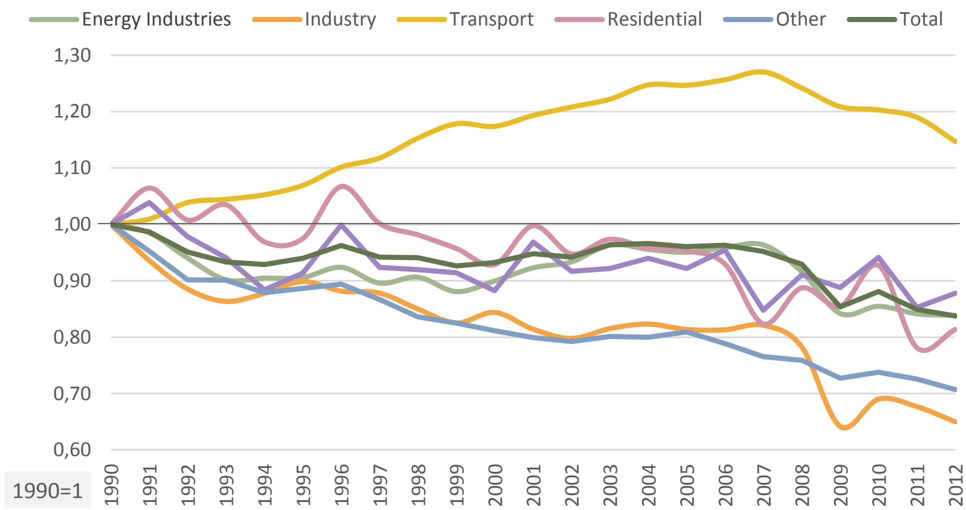

Figure 1. Greenhouse gas emissions by sectors in the period from 1990 to 2012 in EU-28 (adapted from [1])

This makes transport the second biggest emitter of all sectors; however, it comes as no surprise due to the fuel supply profile that characterises the transport sector (see Figure 2). With 95% of fossil fuels in the fuel consumption profile in 2012, of which approximately 85% is imported from outside of the EU borders [1], transport indeed needs a vast transformation in order to establish a security of supply and to meet the renewable energy goals.

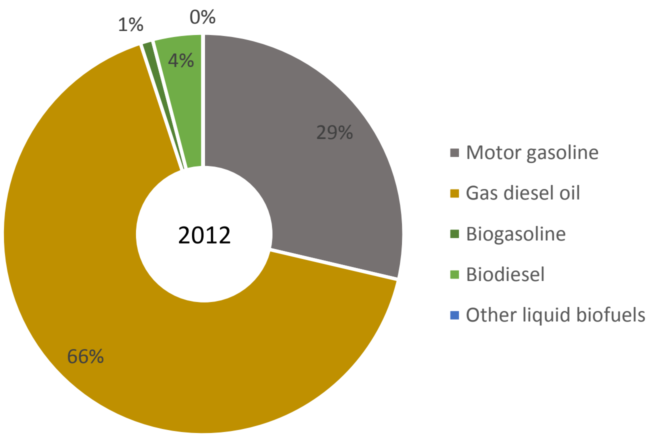

Figure 2. Final fuel consumption for transport in 2012 in EU-28 (adapted from [1])

The conversion of transport towards more renewable energy is tremendously complicated. This is a result of a very complex structure that was established on oil products dividing transport into a variety of modes, needs and technologies. There is no obvious single way in which to solve the problem of the transport sector [2,3]. It is also rather unrealistic to expect that the need for liquid hydrocarbons will be reduced significantly, as some parts of the transport sector, such as heavy-duty long-distance transportation, marine and aviation, are not suitable for electrification. Therefore, the necessity of an alternative solution for this part of the sector has a high priority, especially in 100% renewable systems.

However, in order to find the alternative for the heavy-duty part of the transport sector in 100% renewable systems, it is important to understand how these systems function in relation to the existing systems. Today's energy systems are relatively simple. The energy sectors function mostly individually, and the high share of demands in the systems is met by fossil fuels. These fossil fuels are provided in different fuel forms that can be stored on a large scale. This allows the production to follow the demand, where fossil fuels are acting as storage agents, which offers a lot of flexibility to the system. This flexibility is a crucial characteristic that allows the system to run smoothly with a fast demand response. If the fossil fuels are to be removed from the energy system, then there is a challenge to find solutions in systems with a high share of fluctuating renewable energy that can offer the same or even higher flexibility in energy supply. The current energy systems can technically integrate 20–25% of the fluctuating resources [4]. However, in order to reach the 100% renewable energy system, a rethinking of the whole energy system design needs to happen to be able to manage the variety of renewable energy technologies and to integrate their production profiles so that the end-use demands can be met. This can be done by the Smart Energy System concept, which introduces the cross-sector approach that is very important in reaching the goal of 100% renewable energy systems [4,5]. This concept transforms the linear approach of today's energy systems, where the fossil fuels are directly converted in the part of the system when needed, to a more coherent approach that offers the flexibility to the system by combining different sectors through different conversion and storage technologies. This approach is compensating for the lack of flexibility of fluctuating renewable energy, as it creates the flexibility within the system and not on the resource side. The Smart Energy System concept was used throughout the dissertation in order to find alternatives for transport, which can provide the flexibility to the system by enabling grid balancing and storage options.

1.2 The biomass limit and transport in 100% renewable energy system

The only direct supplement for fossil fuels within renewable resources is biomass, as it can be used in three forms: solid, liquid and gaseous. Due to this, biomass has been seen for many years as a silver bullet for removing fossil fuels from the total fuel consumption. Biomass has been used historically as a fuel and it is not a novelty idea. However, going back to biomass as a main fuel source would eventually create the same problem as the oil dependency today, implying that the variety of technologies should be prioritised instead of focusing on the one solution. The renewable nature of biomass is not the same as the renewable nature of wind, solar or wave energy. Biomass is the only renewable source that can technically be depleted. There is no doubt that biomass will play a major role in future energy systems; still, biomass potential is limited and the sustainable use of it is necessary in order to avoid severe consequences to forest resources and food supply. As desired fuel in all energy sectors, the use of biomass needs to be prioritised to where it is needed the most. In their comprehensive review on bioenergy potential, Dornburg *et al.* [6] have reported a wide range of biomass potential from 0–1500 EJ/year, while their analysis showed that the potential for 2050 is 200–500 EJ/year. The wide range shows the uncertainty of available data that should indicate to what extent it is possible to use biomass resources, and proves that biomass cannot offer a solution for all energy sectors. According to Wenzel [7], there is a need to break a biomass bottleneck as the fossil-free energy systems cannot be relying on the biomass alone.

In order to meet the demand in the parts of the transport sector that cannot be electrified, it is crucial to find the alternative to energy-dense hydrocarbons. As an apparent solution to these problems, biofuels have been promoted. Biofuels were introduced as an alternative at the beginning of the 2000s, and have been surrounded by controversy ever since. The actual effect on the environment, land use changes, and interference with food supply are leading the debates and have been reported and discussed in a vast amount of literature [8–12]. Still, they are recognised as a promising alternative by policies, and the target of 10% of biofuels needs to be met [13,14]. The alternatives for transport have been studied intensively over the last two decades. Most studies have tended to focus on comparison of fossil fuels and biofuels [15,16], different types of biofuels [17], single fuel solutions such as dimethyl ether [18], methane, and methanol [19–21], or synthetic diesel using the Fischer–Tropsch process [22]. When talking about transport as a part of 100% renewable energy systems, the complexity of transport becomes even more challenging. In order to reach the goal of 100% renewable transport eventually, it is important to keep the alternative options open as a means of diversification from fossil fuels. However, by being able to use only renewable energy in order to meet the demand, even with utilised biomass potentials for transport fuel production, there will still be a missing gap to cover the need of the sector [23]. Biofuels as one of the options can help the switch to renewable transport and to expand the range of choices available, but their potential is simply not high enough to offer an overall solution for the liquid/gaseous demand in the sector, especially in the case of the EU [24]. This does not imply that technologies such as second-generation biofuel should be disregarded, but rather that their applications and support programmes are adjusted to their potential. Nevertheless, there is a space for using these and similar technologies for smaller applications in the transport sector. Other renewable technologies such as hydrogen require extensive infrastructure changes, which is one of the main slowdown factors and explains the barely noticeable implementation of this technology. Apart from the extensive changes in the infrastructure, it is important to consider the consumer behaviour when introducing new technologies, including their willingness to adapt to and pay for the suggested alternatives [25,26].

Storage is particularly important in 100% renewable energy systems, as it enables integration of renewable energy sources. In the heat sector, using combined heat and power (CHP) and a large-scale heat pump in combination with thermal storage enables an efficient short-term integration of renewables. Long-term storage and flexibility can be achieved by using a gas grid and liquid fuels. The long-term storage that currently exists in transport needs to be replaced, and finding a solution that can also provide flexibility and balancing capacity for fluctuating electricity is preferable. Liquid fuels used today are complex hydrocarbons, consisting primarily of carbon and hydrogen. The concept of merging carbon sources with hydrogen produced from water electrolysis opens a way for new renewable alternatives for the transport sector. This is of special importance in 100% renewable energy systems, where the cluster of different technologies needs to be used as a balancing capacity that will enable an extensive penetration of fluctuating sources into the grid. This fuel production process enables electricity storage in gas or liquid fuel form by converting the electricity through electrolysis into hydrogen that is later reacted with the carbon source and, in the last stage, converted to any desired fuel. This opens a door to fuel storage, upon which current energy systems are built. By using electrolysers, fossil energy is substituted in a different way, by redirecting the excess electricity produced from renewable sources to the transport sector. Electrofuels offer a solution for transport sector demand while, at the same time, providing flexibility in terms of system regulation.

By introducing the electrofuels as part of the Smart Energy System, we also change the role of transport fuels in comparison to the role they had in a traditional system (see Figure 3). The transport demand in a traditional energy system is supplied by fossil fuels such as petrol and diesel, and these fuels are the primary source of flexibility. The transport demand in a Smart Energy System is met by conversion of fluctuating renewable electricity to liquid or gaseous fuel that can be stored when needed, as was elaborated before. However, we can see that the role of these fuels now is more complex, as their production process offers the integration of electricity and transport sectors, whereby creating the flexibility for the system. Therefore, the flexibility as such is created in the conversion processes and the system is no longer completely based on the resource flexibility.

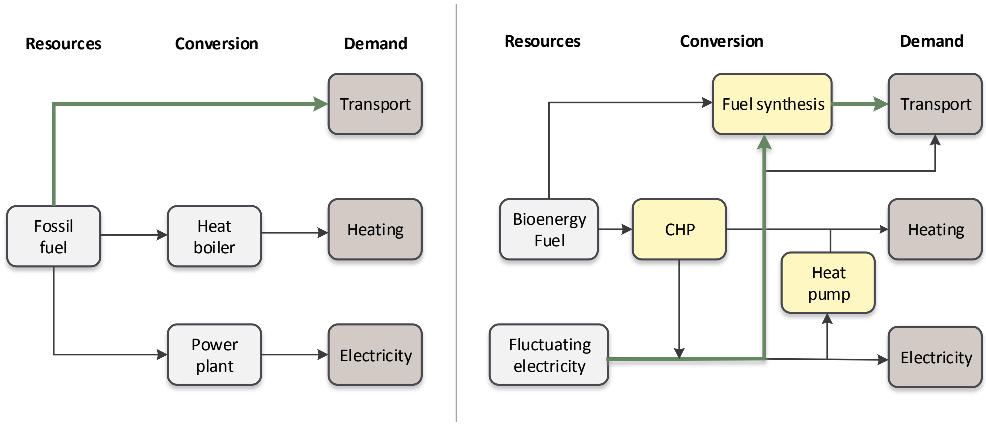

Figure 3. A simplified sketch of a traditional energy system and integrated/smart energy system

This dissertation presents three electrofuel pathways that are produced with the combined use of electrolysers and a carbon source. The carbon source could be emissions, e.g. CO_2 emissions, which are seen as a long-term solution, or liquefying biomass that was previously gasified and upgraded with hydrogen from the electrolysis. Throughout this dissertation, the terms *CO_2 electrofuels* and *bioelectrofuels* are used in accordance with the practice of the research group where analysis was conducted. A detailed explanation of the terminology used will be elaborated below.

1.3 TERMINOLOGY FOR RENEWABLE FUELS BY CONVERSION OF ELECTRICITY - SYNTHETIC VS. ELECTROFUELS

Differentiating between terminologies for fuels in future energy systems is not a key concern today, but in the future when new emerging technologies will be more integrated in the system, such as electrolysers, it will become more significant. It should be noted that the need for terminology clarification emerged in the later stage of study, as it became more obvious that different terms were used interchangeably. Therefore, the publications published before have been using the term "synthetic fuel"—this was not changed afterwards. The terminology was investigated by conducting a review (see Appendix I) and this section summarises the results.

Firstly, it is important to distinguish between renewable and alternative fuels. These terms should not be used interchangeably as they do not necessarily refer to the same type of fuel. Renewable fuels use renewable energy for fuel production, which includes a variety of fuels mostly based on biomass or other renewable energy sources [27], whereas alternative fuels are any alternative to gasoline without the restriction of a feedstock origin [28]. The focus of this dissertation is on renewable fuels as the topic is finding transport fuel options in 100% renewable energy systems.

In this dissertation, the term *electrofuel* is used to define the production process of liquid or gaseous fuel that stores the electricity via electrolysis and the carbon source into valuable fuel products. However, there seems to be no clear definition of what term should be used to describe the previously presented fuel production process according to the literature review (Appendix I). There is also low coherence between terms that are used in the projects with demonstration and commercial plants producing these fuels. Terms such as e-fuels, PTL (power-to-liquid) fuels, synthetic fuels, blue fuels, and Vulcanol are used to describe the same type of fuel. It is necessary to establish a common term in order to avoid misunderstanding and to have a clear distinction in the terminology that reflects differences in the production processes. This is specifically important when discussing about regulatory perspective and supports for technological development. The two most commonly used terms in the literature for the production process of interest are *electrofuels* and *synthetic fuels*. In the literature, synthetic fuels usually refer to xTL processed fuels, and using this terminology should be kept within the scope of the Fischer–Tropsch fuels that are produced by gasification of coal, natural gas or biomass. The term *fossil synthetic fuels* should be used for fuels that use coal or natural gas as a feedstock, while fuel produced by the biomass-to-liquid process can be referred to as *renewable synthetic fuel*. In order to differentiate between the resources used for the fuel production, the abbreviations CTL, GTL and BTL should be encouraged.

Electrofuel as a term emerged from the purpose of these fuels that are used as a storage buffer for renewable electricity. Electrofuels are storing electricity as chemical energy in the form of liquid or gaseous fuels in xTE processes (coal-, biomass- and emission (CO_2)-to-electrofuel). In order to differentiate between the resources used for electrofuel production, the abbreviations CTE, BTE and ETE should be encouraged. The electrofuels are beneficial for future energy systems with a high share of excess electricity and volatile character of the renewable sources, as they give a possibility of storing electricity and balancing the system. Electrofuels therefore have a significant use for electricity in the production process. This is the key difference between the synthetic fuels and electrofuels. This production process can enable renewable energy penetration above 80% [29] as it creates a large amount of flexibility in the system, whereas if synthetic fuels are used, this flexibility would not be possible and the maximum penetrations of fluctuating sources would be approximately 50–60% [4,29,30].

It will consequently become essential in the future to differentiate between synthetic and electrofuels as they have a very different impact on the energy system around them.

1.4 Role and potential application of electrolysers in Smart Energy Systems

Electrolysers can be used both as a conversion and as storage technology. When used as a *conversion technology*, electrolysers are converting electricity into hydrogen or synthetic gas (syngas) that can be used further on. When the purpose is to store electricity, the combination of an electrolyser and the rest of the technologies for electrofuel production is defined as a *storage technology*. In the 100% renewable energy system, both electrolyser purposes are utilised and the electrolyser can act, at the same time, as a conversion and storage technology. These two technologies should be typically differentiated when designing a smart energy system as their purposes are connected to different balancing mechanisms, conversion of various demands or are storing different forms of energy from one hour to another.

Different types of electrolysers can be used for electrofuel production: alkaline, polymer exchange membrane (PEM), and solid oxide electrolysis cell (SOEC). They are differentiated based on the type of the electrolyte used and the operating temperature. Water electrolysis is widely studied and reported, e.g. Smolinka, Carmo *et al.*, Millet and Grigoriev, etc. [31–33]. The alkaline electrolysers are most commonly used as they have been commercialised for many years and the use of advanced alkaline electrolysers is competitive with PEM electrolysers [34]. High-temperature electrolysis seems to be very promising technology as its efficiency is higher due to the high temperature allowing fast kinetics. Recent reviews of the literature on this topic [35,36] confirm the advantages of using electrolysers with solid electrolyte in relation to efficiencies; however, very limited data is available on the durability of these types of electrolysers. Commercialisation of the SOEC technology is yet to come, but the pilot plant was inaugurated at the end of 2014 [37]. The SOEC, compared to other types of electrolysers, conducts oxygen ions enabling CO_2 electrolysis and co-electrolysis of CO_2 and water. This characteristic could potentially be beneficial for production of electrofuels. The SOECs are the focus of analysis in this dissertation, due to their high efficiency and capability of combined electrolysis of carbon dioxide and water for direct production of synthetic gas. As for the high temperature, a further increase in efficiency can be achieved by pressurising the modules [38]. If operated at high pressure, the SOEC can be better integrated in the fuel production process as the synergies between chemical synthesis and the electrolyser are improved [39]. All three mentioned technologies were compared based on their current status and potential future development in [40], and are further elaborated in Chapter 6.

The design and development of SOECs will be a challenge in upcoming years, but even if they do not reach the predicted development levels and the demonstration units fail to perform, this should not stop the deployment of electrofuels. The use of alkaline electrolysis, as well as established technology, for electrofuel production is proven [41] and should be prioritised in case more efficient and potentially cheaper SOEC cannot be used.

1.5 Role of electrofuels in the Smart Energy System

The drivers for radical technological change towards electrofuels are limited infrastructural changes necessary for utilisation of these fuels, reduction of carbon emissions, and a long-term storage option. Harmful effects of greenhouse gas emissions on global warming are a major challenge from today's perspective, but will also have a strong focus in the future. The possibility of converting carbon dioxide emissions into fuels is very important for humankind as it offers a solution for two major challenges: mitigation of harmful emissions and providing security of supply for the transport sector at the same time. The security of supply is a global problem. Many nations are highly dependent on imported oil products, as the geographical distribution of oil resources is vastly uneven and half of the conventional oil is concentrated in the Middle East region [42]. Due to the instability of this region, it is urgent that the security of supply be established. The electrofuels could potentially enable security of supply as the biomass resources and CO_2 emissions are globally more evenly distributed. The aim of electrofuels is to enable the cross-sector integration, integrate more fluctuating renewable resources in the system, and minimise the use of biomass for the transport sector or, in some cases, even eliminate it.

The principal difference between electrofuel pathways is in the carbon source. The bioelectrofuels are produced with an aim to minimise the use of the biomass resource by upgrading it with hydrogen. Biomass is firstly gasified and the produced syngas is upgraded with hydrogen in the hydrogenation process. The hydrogenated syngas is then transformed to the desired transport fuel. This way of fuel production is more efficient than conventional biofuel production, as it reduces the demand for biomass by upgrading it with hydrogen and concurrently enables the integration of the wind in the system. Bioelectrofuels can pave a way for the next phase of energy system conversion, where the biomass is phased out from the transport sector and CO_2 electrofuels are produced. The CO_2 electrofuels create a strong connection between energy sectors, as they recycle carbon emissions from stationary sources such as energy or industrial plants to produce fuels for transport. The production of CO_2 electrofuels by recycling is prioritised over bioelectrofuels due to the previously mentioned issues related to biomass as a resource. This is just another approach to using energy sources in a more coherent way by using different technologies to enable capturing and storing of energy. In the future, capturing of CO_2 from the air will most likely be possible [43], offering recycling of emissions from non-stationary sources and even the accumulated atmospheric carbon emissions. The CO_2 electrofuels are not tied directly to biomass resources; thus, they can theoretically meet fuel demand. This is correct in cases where there is enough carbon in the energy system, which can potentially become an issue in the 100% renewable energy systems, where biomass will be the only carbon source out of renewable resources. The CO_2 electrofuels can be produced with two fuel production cycles. The difference is in the type of electrolysis process used: water electrolysis or co-electrolysis. When using water electrolysis, recycled CO_2 emissions are reacted with hydrogen produced with electrolysis, creating syngas that is converted to fuel through a fuel synthesis process. In the case of co-electrolysis, a combined carbon dioxide and water electrolysis is done and the generated synthetic gas (consisting mostly of carbon monoxide and hydrogen in this case) is processed to the desired fuel.

The main fuel outputs considered are methanol and dimethyl ether (DME) as liquid fuels and methane as gaseous fuels. These fuels are deemed the most appropriate, but many other fuels could also be produced with this fuel production cycle. The suggested alcohol and ether fuels are suitable alternatives for petrol and diesel respectively. The advantage of methanol and DME is that the required changes in the infrastructure are limited and typically connected to alteration of the vehicles and existing fuelling stations. The methane is used as the gas-based transport is often proposed as an alternative in the future [27,28] and the gas vehicles are already present in the transport sector. The benefit of electrofuels is that all pathways finish with chemical synthesis, meaning that the produced syngas can be converted to various fuels and adjusted to the demand side. This flexibility is important as, eventually, the fuel deployed in the transport sector will depend on the investments—both in the technologies for the fuel production and in the infrastructure, predicted technological development, and vehicle efficiencies.

1.6 CURRENT STATUS OF ELECTROFUELS AND RELATED TECHNOLOGIES

The last five years have witnessed a growth in patterns on conversion of CO_2 to methanol. In 2011, the first emission-to-liquid plant (ETL) was commercialised in

Iceland. The plant was named by Nobel Prize Laureate George Andrew Olah, a promoter of the methanol economy [44,45] and owner of a patent on chemical recycling of carbon dioxide to methanol or DME. The plant is recycling the CO_2 emissions from a geothermal power station producing 5 million litres of methanol per year, and the plant owners plan to build larger commercial plants of 50 million litres, which can be exported as a turnkey solution. A new emission-to-liquid project started at the Lünen power plant in January 2015 with a budget of €11 million, which was funded partially by the Horizon 2020 research programme. The project involves Mitsubishi Hitachi Power Systems Europe, the Laboratory of Catalysis and Reaction Engineering of the National Institute of Chemistry Slovenia, the Cardiff Catalysis Institute, Carbon Recycling International, the University of Genoa, the University of Duisburg Essen, i-Deals, and Hydrogenics. The plan is to build a demonstration plant that will start operations in 2017 [46]. A similar concept to the one from CRI is used by Air Fuel Synthesis [47], extracting carbon dioxide from the air and mixing it with hydrogen from water electrolysis. The demonstration unit was commissioned in 2012 [48] with a plan to build a commercial plant in the period of 2015–2020. The Canadian company Blue Fuel Energy has started with the same idea of producing fuel from carbon dioxide and hydrogen; however, it seems they have changed its primary concept. The production of hydrogen for FCEVs (fuel cell electric vehicles) and conversion of produced methanol to a reduced-carbon gasoline are based on natural gas and renewable energy [49]. Ongoing FP7 project SCOT (Smart CO_2 Transformation) [50] is aiming at developing a Strategic European Research and Innovation Agenda for carbon dioxide utilisation (CDU), with one area of focus being the transformation of CO_2 to fuels.

Germany is very active in power-to-gas technologies (P2G). The project of converting carbon dioxide to methane started in January 2014 and the idea behind it is to see how the storing of electricity to gas handles the 100% renewable energy scenario [51]. Two of the partners—ETOGAS GmbH and ZSW—developed the world's largest power-to-gas plant with a capacity of 6 MW_{el}, generating 3 million cubic metres of methane per year in collaboration with Audi [52]. In November 2014, sunfire GmbH inaugurated a power-to-liquid plant, using high-temperature water electrolysis for generating hydrogen and carbon dioxide to produce blue crude that is further converted to diesel [37]. The project is using solid oxide electrolysis cells (SOEC) for steam electrolysis. It is the first plant of its kind integrating these specific electrolysers in the production cycle. The Karlsruhe Institute of Technology (funded by FP7) started a 3-year project with six partners on high-temperature electrolysis and methanation for power-to-gas production [53].

There are also many activities on biomass gasification technology for fuel production, with Sweden being a leader in biomass-to-fuel production. Production of DME and methanol from black liquor started in 2011 under the bioDME project [54] that was financed by the FP7 programme and Swedish Energy Agency. VärmlandsMethanol AB is developing a biomass-to-methanol plant that gasifies biomass residues, with the planned production starting this year [55]. There are two planned projects with paper pulp mills production of biomethanol based on black liquor gasification and wood gasification [56]. An on-going project, which started in 2013, involving Haldor Topsøe, Danish Technological Institute, Skive District Heating, and Chimneylab Europe will test a pilot reactor for the catalytic purification of gasified biomass for heat and power production, but also for liquid fuel production, which would allow Haldor Topsøe to establish biomass-to-liquid technology [57].

While the previously mentioned projects and activities are focusing mostly on the technology for the fuel production, there have also been many projects aiming at deploying methanol and DME as transport fuel. Project SPIRETH [58], which had joined Denmark, Sweden and Finland with the main goal of testing methanol and DME as shipping fuels, finished at the beginning of 2014. The project results have shown that it is feasible to use methanol and DME for marine transportation and that it is possible to retrofit the ship's main diesel engine to run on these fuels. TEN-T project "Methanol: The marine fuel of the future" is an ongoing project that is finishing in December 2015, and includes the pilot testing of methanol on the passenger ferry Stena Germanica [59]. It can be seen as an extension of the SPIRETH project as some of the partners in the projects are the same. If this conversion of Stena Germanica is successful and it becomes the first passenger ferry on methanol, further conversion of up to 25 ferries will be done until 2018. In Denmark, three companies created a Green methanol infrastructure (GMI) consortium funded by EUDP. The project is running from September 2013 until February 2016 and will focus on the development and demonstration of refuelling infrastructure for methanol—it will result in up to three methanol filling stations [60]. As methane has already been demonstrated as transport fuel, with 10 million vehicles worldwide [61], no specific projects were presented here.

As was noted above, considerable progress has been made with regard to demonstration and commercialisation of electrofuel production, biomass gasification, and methanol/DME deployment. It is posited that this could accelerate the deployment of electrofuels in the future energy systems.

2 RESEARCH QUESTION AND READING GUIDE

By moving the focus from one sector or one technology to the overall energy system, it is possible to maximise the synergies in the system. However, exploiting the synergies cannot happen without understanding how single technologies can enable the flexibility in the system, which will help the resources and cost-effectiveness of the 100% renewable energy system. The aim of this dissertation is to investigate the feasibility of renewable fuel pathways that can be utilised in 100% renewable energy systems, and to further the current knowledge on electrofuels. The electrofuel pathways are presented and investigated, both from the fuel production process itself and from the possible application of the fuels in the energy system. Electrofuels are considered an interesting solution for the transport sector as they help cross-sectorial integration in the energy system, offer a solution of electricity storage in the fuel form, thus helping system balancing, and enable fluctuating renewable resource integration. These characteristics were evaluated in order to analyse the feasibility of these fuel pathways, and the following research question is formulated:

"Are electrofuels a feasible element of a 100% renewable energy system?"

In order to answer this question, the analysis is divided into six parts:

- Investigation of electrofuel pathways;
- The individual stages of the production cycle and the related technology status of the components;
- Ability of integration of fluctuating renewable resources;
- Fuel production costs, including the cost of system balancing;
- Socio-economic cost[1] of the pathways as part of the 100% renewable energy system;
- Public regulation and initial roadmap for deployment of electrofuels.

To be defined as a feasible element in a 100% renewable energy system, it should contribute to the system's flexibility by enabling the integration of fluctuating resources. The production costs should be competitive with other options, and the overall socio-economic costs of the element as part of the system should be comparable with other alternatives or preferably lower. These are three main defining factors for answering the research question.

The different parts of the analysis were conducted through the following publications. The preliminary feasibility study on different pathways that can create alternatives for

[1] The socio-economic costs include investments in the energy system, investments in the transport sector, overall operation and maintenance costs, and fuel costs for the system.

supplying the transport sector was presented in *'The feasibility of synthetic fuels in renewable energy systems'*. This paper also investigated the ability of these pathways to integrate fluctuating renewable resources, and the sensitivity analysis based on fuel costs was performed. The follow-up on this paper was made with a newer version of the energy system analysis tool. The subsequent paper—*'Synthetic fuel production costs by means of solid oxide electrolysis cells'*—determined the fuel production price for different types of fuels, which included comparative analysis with certain types of biofuels. The paper *'A comparison between renewable transport fuels that can supplement or replace biofuels in a 100% renewable energy system'* presented a comparative analysis of seven different fuel production methods, and provided insight into pathways creation, their energy flow diagrams, and production efficiency.

2.1 DISSERTATION STRUCTURE

This dissertation is divided into 10 chapters, including *Introduction* and this chapter. *Chapter 3* is placing the research in context by presenting the current status of the alternative fuels technology, the choice awareness among them, and the need to look into the transport sector as part of the overall system and not as an isolated sector. A methodological framework is described in *Chapter 4*, explaining the Smart Energy System concept that is the foundation for this research. The chapter also includes a description of the feasibility study design and diamond-E framework that enabled the overview of the concerns that the feasibility study needs to include. Moreover, explanation of the energy system analysis tool used for performing the feasibility study and data collection is presented. *Chapter 5* outlines different pathways for electrofuel production and the main consideration included in their formation. The next chapter looks into system architecture elements, including a detailed review of the production steps, together with the chosen fuel properties and the infrastructural changes necessary for the implementation of electrofuels in the system. The feasibility study of electrofuels is performed in *Chapter 7*. This chapter includes the results of socio-economic and technical analysis, results of fuel production costs, and sensitivity analysis of the results. *Chapter 8* begins with an overview of the actors included in EU legislation creation, gives a historical summary of the policies within alternative fuels, and finishes with implications of the existing policies on electrofuels. *Chapter 9* presents the roadmap for deploying electrofuels in the transport sector and the needed steps to do so. Finally, *Chapter 10* summarises the findings of this dissertation and the answers to the research objectives.

3 THE RESEARCH IN CONTEXT

Seeking the answer to why certain fuel alternatives are highlighted, promoted or implemented, while others are not, is a crucial step in the understanding of how to implement the radical technological change necessary for the shift to a 100% renewable energy system. The search will try to identify where policies did not recognise electrofuels or Carbon Capture and Recycling (CCR) as potential alternatives in the climate mitigation and set up renewable energy goals, as well as how this is reflecting on solving the transport sector transition to renewable energy. The theoretical strand used to find this answer is introduced by Lund in *The Choice Awareness Theory* [5]. The theory is concerned with the implementation of radical technological change. The radical technological change is defined by Hvelplund [62] as a change of more than one dimension of technology—technique, knowledge, organisation, products and profit—and the degree of radical change increases with the number of dimensions changed. The Choice Awareness Theory creates a concept in which individuals and organisations can manipulate the choice awareness in creating a perception that certain alternatives do not exist, which leads to no radical technological change being implemented. This is a result of the elimination of technical alternatives that are not supporting existing organisational interests. This arises because the existing organisations will tend to seek the options that are applicable in their structures and ideologies. The perception of choice can be manipulated by individuals and organisations, and secondarily by the political agenda, which can lead to the perception of no choice, which is not true according to the theory.

This theory is well suited to the problematics of no choice in the transport sector, or restricted alternatives proposed, in order to compensate for the depletion of oil and to reach goals set up by policies. This chapter seeks to investigate whether there was a choice elimination within alternative fuels for the transport sector. The Choice Awareness Theory is supported by the theory on technological and political lock-in, and will be elaborated in detail below.

3.1 UNPACKING THE CHOICE AWARENESS OF ALTERNATIVE/RENEWABLE FUELS

The European climate and renewable energy policies imposed obligations towards Member States in order to reach the desired targets for emission reductions, implementation of renewable energy, and energy efficiency measures. Apart from these EU obligatory targets, Denmark had a more ambitious agenda as the Danish Government had a long-term vision of Denmark being free of fossil fuels. In order to reach that vision, it will be necessary to rethink the design of the energy system and switch to a more coherent approach that interconnects different parts of the energy system. This would imply that the energy system would have to go through a radical technological change in order to convert to 100% renewable energy. The radical technological changes will appear in all sectors, and with transport being one of the most complex and challenging parts of the energy system, completely relying on the oil, a problem of finding a solution to meet these goals became inevitable. The desired energy security, reduction of GHG emissions, and economic development are the main drivers for policies promoting renewable energy in all energy sectors. As a Member State, Denmark has to follow the EU policy framework that also included the options for the transport sector. The European policies on alternative fuels are presented in detail in Chapter 8, but the problem is going to be discussed here in relation to the theories. It is important to note that the European Directives do not contain the means of application, but rather impose the requirement to reach the goals with any forms or means [63]. This correlation between Danish action and EU Directives is interesting to mention because of the flexibility that Directives give to the Member States.

The transport alternatives gained the interest of the European Union at the same time the political agenda was strongly focusing on climate change in the early 2000s. This was directly related to the EU not progressing well in emission reduction [64], set up by Kyoto emission targets, and transport being the sector with a constant emissions rise became attractive. As a large proportion of transport demand will continue to rely on liquid hydrocarbons due to specific modes and needs of parts of the sector, biofuels are recognised as necessary to meet this demand by policymakers [65,66]. With the policy development over the years from 2001, when the first proposal for a biofuel directive was issued until today, it is noticeable that the focus within the alternatives is given to biofuels. The promotion of biofuels has transformed into a regulatory framework containing mandatory targets for introducing these fuels to the European market [13,14]. With a goal of 10% biofuels by 2020, the European Union has imposed the obligation to integrate these fuels in the transport sector. Until 2006, Denmark as a Member State did not have many activities on how to solve the transport sector problems. In 2006, Lund and Mathiesen stressed that the transport sector would undermine Denmark's attempt to lower the CO_2 emissions [67]. This report was followed by Mathiesen *et al.* [2], which looked into integrated transport and renewable energy systems. The report concluded that the approach for solving the complexity of transport is to use different technologies, and that relying on one fuel type will not solve the problem. In 2009, the IDA Climate Plan 2050 presented detailed analysis of the transport sector and the way in which to establish a 100% renewable energy system [68]. In 2010, the Danish Commission on Climate Change Policy launched their report [69] on how to reach 100% renewable energy in 2050, which stressed the problems with biofuels: *"Several problems are associated with biofuels, primarily climate impact and scarcity, and these make it problematic, at present, to base a future strategy for the transport sector on biomass alone."* This is in line with how finding a solution for renewable fuels does not have to put the restriction on the choices. The Danish approach differs from the European as the focus is on the whole system and its integrations, while the most common approach is to focus on singular sectors or even disregarding some parts of the system. Nevertheless, Denmark is obliged to reach the targets of the EU first, and hereafter explore the possibilities to fulfil additional national targets. The choice perception of alternative fuels in this chapter will therefore be discussed at an EU level.

The main focus is on liquid or gaseous fuel alternatives as they can be deployed for freight transport, but others will be mentioned as they are part of the EU legislation. The perception of no choice has appeared many times during the last 15 years of EU alternative fuel policies as some choices were excluded from the agenda. Just recently, during the conference "The role of biofuels in achieving the EU's climate goals for 2030 and beyond" in November 2014, Mr. Reul, as a Member of European Parliament, stressed that "*fulfilling ambitious European goals will be very expensive and cannot happen without biofuels*" [70]. The message is clear: there is no other choice for reaching the European goals, but by using biofuels. The biofuels are defined by Directive 2003/30/EC [27], which includes a list of different fuel outputs that should be considered as biofuels. The list is rather extensive but it includes all fuels that are produced from biomass. According to the European Environment Agency's Scientific Committee opinion from 2008, even the currently assigned EU goals of 10% of biofuels cannot be met sustainably [71]. Even if the use of second-generation biofuels is included, the imports of biofuels are inevitable, which represents a problem of monitoring the sustainable production of biofuels outside of Europe. However, the perception is that the biofuels are most likely able to meet the targets; thus, there is no focus on other non-bio alternatives or more complex production cycles. The focus on one technology is explained by Arthur [72], clarifying that one technology can exercise the exclusion of the others due to the competitive nature, and if it has a large proportion of adopters, then that technology has an advantage, which can consequently lead to a no-choice perception. The consequences of biofuel support programmes can be seen in the example of first-generation biofuels that are difficult to scale down, even though they have turned out not to be the sustainable option for transport [73]. Therefore, further policy developments need to be more flexible for different alternatives.

In spite of considerable controversy surrounding the biofuels over the years due to biomass scarcity and other issues related to their production, e.g. land use issues [8], interference with food supply [74], and other impacts on the biosphere and environment [75], the message is not changing. The Commission stated: *"The use of renewable energies (wind power, solar and photovoltaic energy, biomass and biofuels, geothermal energy and heat-pump systems) undeniably contributes to limiting climate change."* [76] This information is not completely correct. While some of the renewable energy does contribute to limiting climate change, biofuels are not always one of them. The past political agenda has selected certain results from Life Cycle Assessment (LCA) studies that resulted in policies that assume that biofuels are carbon-neutral. The assumption used is that the end-use CO_2 emissions are balanced by the CO_2 uptake that occurs during the feedstock growth. This assumption was proclaimed as incorrect by the European Environmental Agency in 2011 [77], which is 10 years after the introduction of biofuels in the policies. The pitfall of the policy assumption has been clearly recognised by DeCicco [78]. The author indicates that there is a misunderstanding regarding the carbon mitigation challenge, and that there should be a refocus on achieving CO_2 uptake through reforestation, rather than a focus on replacing fuels that essentially have the same end-use CO_2 emissions. DeCicco states: "*If there is any climate benefit to biofuels, it occurs only if harvesting the source crops causes a greater net removal of carbon dioxide from the air than would otherwise have occurred.*"[79] The half-true statement that biofuels are carbon-neutral and sustainable is a non-equalised evaluation that promotes only advantages and disregards the disadvantages. This type of statement is often used to promote some solutions; according to Lund, "*a good half-true statement is characterized as a 'part' of the truth that can be communicated and understood easier than a comprehensive view of the truth itself*" [5]. This can be noticed at the beginning of the biofuel and alternative fuel policies, where the negative sides of biofuels were completely disregarded [80,81]. It is crucial that the uncertainties and missing knowledge are highlighted rather than disregarded in the promotion of certain alternatives.

Giampietro and Mayumi [82] have widely investigated the biofuel development and societal delusion within these fuels. They outline three types of lock-in taking place in society in relation to biofuels: the ideological lock-in, the academic lock-in, and the economic lock-in. The ideological lock-in can be described by seeing biofuels as a silver bullet solution that solves the sustainability issues. The academic lock-in is more interesting as there is a large proportion of literature supporting the development of biofuels. The authors explain this as a potential consequence of funds for research and development which are specifically allocated to biofuels. The economic lock-in is related to the private corporations and misunderstanding of what the market should aim for when it comes to alternatives. This could be seen as a consequence of a lot of uncertainties that are making the choice difficult. Furthermore, the current policy decision making involves a multitude of stakeholders, which hinders the economic lock-in due to vested interests.

Oberling *et al.* [83] investigated the investments of 'oil majors' in liquid biofuels. They picture the government policies that impose biofuels as a solution, as a supportive agent for oil companies, as their core business is not much beyond the investments in biofuels. Their analysis showed that smaller producers of advanced fuels face strong technological systemic lock-in, as in order to reach the market they often need to enter the joint venture agreement with oil majors. Mojarro also looked into oil companies and their relation to biofuel production, and discovered that large oil companies such as BP, Shell, and Petrobras have a large amount of biofuel patents [84]. The previously mentioned findings are aligned with Lund's statement: that the alternatives that are fitting well into the framework of existing organisations are preferred [5].

The alternatives are created by the existing organisations and some of the alternatives are left out because they are out of the perception of the actors involved. The alternatives suggested for the transport sector, alongside biofuels, are compressed natural gas (CNG), liquefied petroleum gas (LPG), and hydrogen and electric vehicles. It is evident that neither CNG nor LPG will help emission reduction or are sustainable renewable alternatives. Hydrogen can be a renewable alternative if it is produced from renewable sources [13], e.g. via water electrolysis powered by renewable electricity. The electric vehicles that use renewable electricity have been acknowledged in the final conclusions of the Indirect Land-Use Changes (ILUC) discussion about changing the policy due to the biofuel sustainability issues [85] multiplying the electricity produced by renewable energy by a factor of five for road transport. This, together with new infrastructure requirements [28], is the biggest step for pushing forward electric vehicles. The proposed alternatives are easier to implement with the existing institutional setting, especially CNG and LPG, while some are a bit more complicated, e.g. hydrogen and electricity. As some alternatives can be disregarded, in this case, electrofuels, the choice awareness needs to be raised and citizens and/or universities that would impose radical technological change could do this.

As the electrofuels are based on different technologies that are part of the production cycle, the choice awareness of Carbon Capture and Recycling (CCR) is also of interest. Parallel with the radical technological change happening in the transport sector, as well as the discussion about needed technologies to reach European climate and renewable energy goals, Carbon Capture and Storage (CCS) has been introduced, wherein it "…*may be the only option available to reduce direct emissions from industrial processes*…" [86]. In Denmark, newspaper Ingeniøren has stated in two attempts that the storage of CO_2 is necessary and that we are simply forced to use it [5]. The Commission also states in the Climate Action that *"…global greenhouse gas emissions cannot be reduced by at least 50% by 2050, as they need to be, if we do not also use other options such as carbon capture and storage…"* [87]. According to IEA, CCS is needed technology for climate mitigation: *"…development of CCS, which is necessary to achieve low-carbon stabilisation goals (i.e. limiting longterm global average temperature increase to 2°C)"* [88]. It can be misleading that these formulations are failing to take into account other studies that did not include CCS as a mitigation technology and are still achieving the same goals [89], but statements are giving the perception of no choice [5]. While CCS is perceived as necessary for mitigation of emissions, the CCR (also called Carbon Dioxide Utilisation (CDU)), which recycles carbon dioxide emissions and converts them into valuable products such as transport fuels, chemicals or materials, has been set aside. Jones *et al.* conducted a preliminary study on public perception of this technology, which showed that public awareness of CDU was very low and that people showed scepticism about CDU as a means of fighting climate change [90]. There is a reason to be cautious about the necessity of storing the carbon dioxide, as it is a valuable resource for production of fuel, hydrocarbons, and different products. The CDU is not recognised by new monitoring and reporting regulations of the Emission Trading Scheme (ETS), which indicate that only emissions that are transferred to another ETS installation or injected to geological storage can be deducted [91]. However, there is a possibility of changes that will not exclude future innovations; thus, it is expected that there will be a space for CDU in the future. At the current stage of the technological development, the legislation should embrace both technologies (CDU and CCS) as potential options, which would open a door for emission-to-electrofuels for the transport sector.

With the advantage of a production cycle that finishes with chemical synthesis, the resultant fuels can be adjusted to meet the requirements on the demand side. It is assumed that these fuels will be alcohol or ether fuels such as methanol and DME or methane as a gaseous alternative. However, EU legislation imposes restrictions on the use of alcohol fuels only as light blends in the vehicles. For example, methanol can be blended with gasoline up to a maximum of 3% volume according to Directive 2009/30/EC, while ethanol, as a more common biofuel, can be used up to 10% volume [92]. Both methanol and DME are recognised as oxygenates for petrol. According to the Directive, ethers with five or more carbon atoms per molecule can be mixed with petrol up to a maximum of 22% of the total volume. This confirms that some choices are restricted in the legislation and not explicitly promoted within the existing framework. As a result, the availability of these fuels is very low. This is an especially interesting outcome for alcohol fuels due to their historical background. At the end of the 19th century, petrol was held as being the least promising option, but today is the dominating fuel source for vehicles, while alcohol fuels were used by Otto as early as 1860. Germany was using methanol fuel as a low blend in the late 1960s [93], and Sweden and New Zealand used it at the beginning of the 1980s [94]. California had extensive alcohol fuel programmes with 20,000 internal combustion engine vehicles that were using high blends of methanol (M85 and M100) and 100 fuelling stations [93]. Today, China has both governmental and provincially supported methanol programmes. DME has also been identified as being a good fuel for compression engines [95–97].

It seems that it is very difficult to escape the lock-in from historically dominating technologies such as the internal combustion engine (ICE). Even with the technological lock-in, there is no need to restrict the alternatives that can be used in the existing technologies, such as different fuel types. However, the technological lock-in should be avoided, as technology such as electric vehicles should not be seen as a competitor for internal combustion engines, but rather as a solution to one part of the transport sector, with the internal combustion engine for another part. There is not a single solution technology to overcome the complexity of the transport sector; the joint forces of the existing and innovative technologies should be utilised to their best.

To sum up, it can be seen from both the fuel pathways supported and the singular technologies supported that electrofuels are not specifically recognised as an alternative for transport. It should be acknowledged that when the current legislation framework proposed the alternatives for transport and when Directive 2009/28/EC [13] was implemented, there were no electrofuel demonstration facilities. This resulted in the targets that mostly focused on biofuels. If interpreting Directive 2009/28/EC [13], then the fuels produced can be acknowledged as renewable fuel only if produced by 100% renewable energy. This means that at the current stage of demonstrating electrofuels, if electricity, as a main part of the fuel, is not produced exclusively from renewable resources, then electrofuels cannot be considered a renewable fuel. This is acceptable for the future but currently this hinders the development of these fuels, as they are not recognised for meeting the renewable energy targets.

As for the studies [9,98–100] that confirm that biofuel goals of 10% are not possible to be sustainably met, the probability of creating a 100% renewable transport sector for Denmark seems completely unrealistic with the suggested fuel alternatives. If the only renewable alternative to fossil fuels for ICE is biofuel, then one can say that due to the scarcity of biomass resources, one will continue to rely on fossil fuels. These findings suggest that comparative studies of alternatives including radical technological changes should be undertaken in order to enhance the awareness of different alternatives for solving the problem in the transport sector. The transport sector has to be looked at as part of the whole energy system, as some alternatives that are beneficial for the sector itself are not necessarily suitable from the overall system perspective. This is especially important in the case of 100% renewable systems, where specific profiles of renewable energies have consequences on the system level. It is difficult to predict the future, as well as the technological development that will happen; therefore, the possibility of choice between different alternatives is important, as one of them could be the right one. However, one cannot guarantee that this will happen, and there is a possibility that none of the options will satisfy the needs in the future.

4 METHODOLOGICAL FRAMEWORK AND ANALYSIS TOOL

As was indicated in the previous section, the existing institutional setting has potentially guided the decision making with elimination of some technical alternatives. In order to create Choice Awareness the feasibility study needs to be conducted to find relevant alternatives. This chapter presents the background of the 100% renewable energy system design and the design of the feasibility study. The description of Smart Energy Systems is the foundation for creating alternatives intended for the transport sector, as it is considered essential that the alternatives be analysed as part of the overall energy system. The reasoning behind this is that the energy system needs to be designed with a coherent approach that interconnects different parts of the system, as different parts of the system have an influence on other parts, which cannot be disregarded in the search for best alternatives.

4.1 SMART ENERGY SYSTEMS

Creating a 100% renewable energy system is much more complex than existing energy systems. This is due to the production profiles of renewable energy sources that are fluctuating. In order to maximise their potential within an energy system, different energy storage options need to be used to stabilise the system and to store energy in the hour when electricity cannot be used. Today's energy systems are based on fossil fuels, which are a form of energy storage and are transported around the world in different forms. When transforming the systems towards renewable energy sources, biomass is the only carbon carrier available and can be used in the same manner as fossil fuels today. With the scarcity of the biomass resources and the sustainable use of them, other renewable sources need to be utilised. Therefore, in order to achieve the flexibility of today's energy system, it is necessary to find a way in which to successfully store fluctuating renewable resources so that they can provide the needed flexibility in the system. As the renewable technologies for electricity production are more developed, the focus is often leaned towards the electricity sector itself and solutions for storing electricity. While this approach is beneficial for finding a short-term solution for grid balancing in an extreme situation, the long-term development should focus on the integration of different sectors and types of storage technologies in order to find the most beneficial solutions for the overall system.

The Smart Energy System (SES) concept was introduced by Lund *et al.* [101] and it is defined as:

> *"An approach in which smart electricity, thermal, and gas grids are combined and coordinated to identify synergies between them in order to achieve an optimal solution for each individual sector as well as for the overall energy system"*

The three types of smart grids to create renewable energy systems—electricity, gas and thermal—should never be seen as separate from each other as the coordinated implementation of individual sectors is advantageous for the system. When paired with different types of storage technologies they improve the energy system's flexibility and enable the integration of renewable energy sources (see Figure 4). The smart energy systems are an integrated part of conversion towards 100% renewable energy systems. This approach establishes interconnections between the sectors, resources and demands, which are very important in future energy systems. Therefore, it is important to consider alternative technologies and their impact across the whole energy system, as the consequence of their implementation cannot be seen as separated from the system. Single sector focus needs to be expanded, and a brief description of energy sectors merging in order to reach a 100% renewable energy system is presented below.

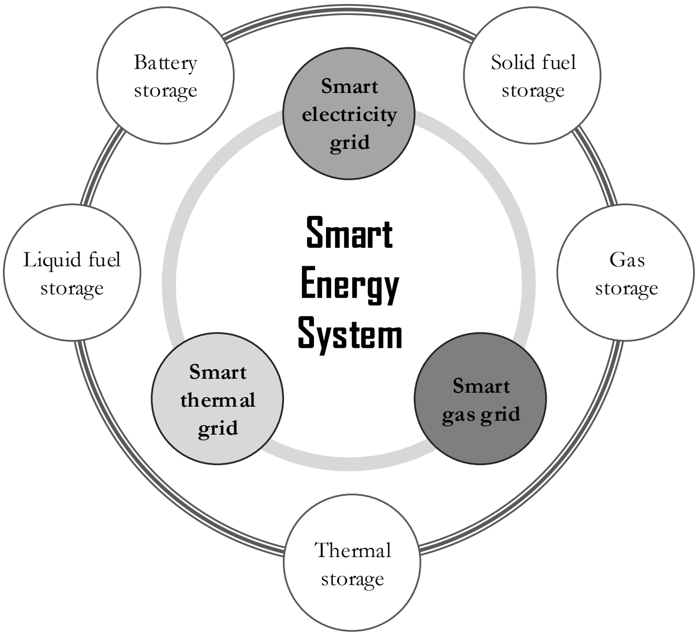

Figure 4. Smart energy system concept

Most parts of the energy system have been widely studied and the next step should be to establish more synergies between sectors based on the knowledge of individual technologies. A number of studies have found that merging the electricity and heat sectors is beneficial to the system [102–105]. This is important as the increasing number of renewable electricity sources reduces the fuels used in conventional technologies, and the system needs to be able to facilitate this by adding technologies that could help the integration. The beneficial technologies for integration of fluctuating renewable energy include CHP plants and large-scale heat pumps that are paired with thermal storage in district heating systems if possible [4]. In cases where district heating or cooling cannot be used the individual heat pumps should be prioritised [30,103,106–109]. This set of technologies enables the integration of renewable energy sources while, at the same time, the biomass consumption is lowered and the boilers for heat production are displaced, meaning that the fuel efficiency is maximised [102,103,110]. Merging electricity and heat sectors not only is good from the system integration point of view, but also can lower the overall costs and increase the value of wind power [40]. Detailed description of these steps can be found in Appendix II.

Going a step further towards 100% renewable energy systems is merging these two sectors with transport. The transport sector should be designed with the maximum utilisation of electricity for transportation in the parts of the sector where this is possible. Many studies have been published on this issue [2,89,111–117] and it was proven that the electrification of the transport sector should have the first priority—in trains, EVs and similar technologies. However, the rest of the sector faces significant challenges for conversion to 100% renewable energy. The integrated approach for introducing more renewable energy into the transport sector is crucial, as there are not many renewable options to cover the need for transport demand such as different types of heavy-duty transport. As a preferable option for the transport sector, biofuels are suggested [27]. This is not particularly surprising, given the fact that biomass, as the only carbon carrier of renewable energy sources, can be converted to high-energy density fuels that can be used in the current infrastructure. As stated earlier, there are many issues with using biofuels for transportation, due to their environmental effect, sustainable use, land-use effect, and the life cycle emission. The fluctuating renewable resources should be used instead of biomass due to the mentioned concerns and resource limitation. It is as important to limit the use of bioenergy in the future energy system as it is to eliminate the use of fossil fuels; the biomass resource potential cannot meet the current use of fossil fuels. In cases where the biomass use is unavoidable for transport purposes, the production process efficiency should be maximised. The conversion of electricity into valuable liquid or gaseous fuels can be done in different ways [117,118], resulting in various types of electrofuels. The number of electrofuel pathways will be further described in detail in Chapter 5. The design of electrofuels as an alternative solution for the transport sector was based on the presented smart energy system approach. While the solution was focused on integrating renewable energy in the sector, it simultaneously provided flexibility to the system. The electrofuels are integrated in the smart energy systems through the smart gas grids, and can be seen as electricity storage in the form of gas or liquid fuels. This way of producing fuels enables storing the excess electricity produced into valuable fuel products that can be cheaply stored and used in the existing infrastructure. The production process converts electricity by using electrolysers in combination with biomass gasification or CO_2. This type of fuel paves the way for completely removing the biomass from the transport sector and converting the CO_2 as a valuable product to fuels for transport. Some elements of the production cycle should be further developed, as the current stage of some electrolyser technologies puts uncertainty on the potential of the technology deployment in the future. On the other hand, there are electrolyser technologies available today that can be used in the production cycle [38,119–121]. Concerning the other parts of the cycle, biomass gasification has a potential to improve, while chemical synthesis is already developed [122,123].

The smart energy system approach is transforming a simple linear approach, fuel conversion for end use, which is characteristic of today's energy systems, to a more coherent and combined approach. By combining energy sectors, the flexibility created across them can compensate for the lack of flexibility that fluctuating renewable resources bring. This highlights how important smart energy systems are when introducing high shares of renewable energy in the system.

4.2 FEASIBILITY STUDY AND ENERGY SYSTEM ANALYSIS DESIGN

When talking about future energy systems and technologies, any methodology can be debatable as the future brings numerous uncertainties. Conducting a feasibility study is an important part of investigating alternative technologies for energy systems—the studies need to be designed to enable the radical technological change. The scope of feasibility studies should be broad and it should answer which alternative option is the most feasible for solving a problem of interest. The feasibility study should be used to raise the choice awareness and should not lead to misuse due to the wrong interpretation of study purposes [124]. As stated before, the technical alternatives need to consider the whole energy system and not only the sector where it will be deployed. This is due to the many interactions between sectors that will be part of future energy systems, as the way in which to deal with the intermittency of the most renewable energy sources. In addition, the alternatives should be analysed with a long-term horizon, as the investments in the energy sector are money-intensive and have long lifetimes, especially infrastructure investments [125]. Even with the long time frame, the short-term fluctuations of the renewable technologies need to be considered to account for the fluctuating nature of these resources and to assure that the demands are met accordingly.

The alternatives should be analysed from the societal perspective and not from the organisational point of view, as the current organisational framework does not reflect the future. Therefore, the feasibility study should be done in such a way that it finds the best solution relatively independent of the existing institutions or regulations. The three-step approach adapted from Lund *et al.* [126] was used to perform the feasibility study: identification of what, for whom, and why it should be studied; design of the content of the feasibility study through diamond-E analysis; and analysis of the created feasibility study.

In the case of electrofuels the WWW analysis can be summarised as follows: *What should be studied?* This concerns the socio-economy of electrofuels. It should be seen as a long-term energy system analysis of alternative transport fuel pathways produced by storing electricity into a liquid or gaseous form. The electrofuels should be understood as a renewable alternative to biofuels in the parts of the transport sector which cannot be directly electrified. *For whom and why should electrofuels be studied?* The study is done for the Danish Government in order to provide recommendations of alternative fuels that could help to meet the renewable energy goal in the transport sector and to reach the 100% RES target in 2050. With restricted biomass resources and the high ambition to reach the target of 100% renewable energy in the Danish system, it is necessary to find alternatives to biofuels as the biomass potential is not sufficient to cover the needs for biomass in all energy sectors. This study is a socioeconomic feasibility study and the purpose is to examine whether the electrofuels are feasible from the point of view of the society as a whole, so it could be said that the study is not only for the Danish Government but also for the Danish society.

By using the diamond-E framework defined by Fry and Killing [127], the consequences of what should be analysed and to what extent are summarised in Table 1. The design of the feasibility study includes four main parts: organisational goals, organisational resources, financial resources, and natural and socio-economic environment. The *organisational goals* of the electrofuel feasibility study relate mostly to the governmental goals that are focusing on the conversion towards renewable energy systems, followed by reductions in greenhouse gas emissions. The governmental goals also include the ambition to strengthen local companies and provide new workplaces, which is very important from a societal perspective. The *organisational resources* are focused on the key characteristics of the current situation which can be linked to the implementation of electrofuels. Denmark has strong research institutions that are analysing and developing the technologies necessary for these fuels, such as electrolysers, gasification, biomass potential, and energy system analysis. Denmark also has a big private company (Haldor Topsøe) that is a main producer of fuel cells, electrolysers, and the chemical synthesis plants, which are the core parts of the electrofuel. It is considered a benefit that Denmark look into electrofuels as an option, as the resources are mostly in place. However, in the initial stage of investment, there is also a possibility of turnkey solutions that could be imported from Iceland or Germany, but a local solution should be preferred in the long term. The technology development that supports electrofuels had some setbacks with closing down the Pyroneer demonstration gasification plant in Kalundborg, even though the technology was proven to be working well. The reasoning was that there were no interested international partners to co-operate on the full-scale plant. This does not necessarily have to be taken as a big obstacle as the plant has not been shut down permanently, but rather until the demand for the technology is present.

Table 1. Diamond-E analysis table that indicates the design of electrofuel feasibility study in Denmark

	Consequences for content of the feasibility study
Organisational goals:	
- Security of supply - To reach 100% renewable energy in 2050 (independent of fossil fuels) - Reduction of greenhouse gas emissions in 2050 (EU objective) - Efficient use of biomass in all energy sectors, including transport – a need for alternatives to it - Strengthen the Danish companies in the field of green energy, and provide new workplaces - Technology assessment for supporting a policy framework for implementing needed transport technologies	The examined alternatives should: - Provide security of supply by using local resources; - Fulfil the renewable requirement in order to meet the 100% RES goal in 2050; - Provide flexibility to the system by integrating fluctuating resources; - Help the emission reduction; - Minimise the use of biomass resources.
Organisational resources:	
- The electrolysis and chemical synthesis plant producer in place (Haldor Topsøe), and research institution in place (DTU on electrolysis, AAU on energy system analysis, SDU on biomass potential)—no final product solution (no demonstration facility) - Step back in biomass gasification technology that can be used for fuel production – closing the Pyroneer gasification plant by DONG - 191,000 unemployed people – regarded as a work resource - Possibility of importing turnkey projects from Iceland or Germany	- It should be analysed to which degree the alternatives utilise the existing resources and technology developers in order to maintain and create more job opportunities; - Research needs should be analysed; - The possibility of importing turnkey projects should be analysed; - Need for further research and demonstration on the technology before concrete implementation.
Financial resources:	
- Danish governmental funds for transition to a 100% renewable system (wind expansion, strategic energy planning, etc.) – all initiatives in the government's strategy are financially supported - EU funds for alternative fuels and transport technologies such as Horizon 2020	- Examine the possibility of getting financial support, and provide the economic analysis of the alternative (which should not be a deal breaker)
Natural and socioeconomic environment:	
- High dependency on oil – providing security of supply - Renewable energy system goals - No other renewable alternative for ICE, apart from biofuels being promoted by EC or EU policies in place - Public strategy giving the support for developing and commercialising electrolysers - No support for Carbon Capture and Recycling (CCR) for recycling carbon into commercially viable products such as fuels or chemicals. On the contrary, Carbon Capture and Storage (CCS) is seen as an inevitable option for reducing carbon emissions by treating carbon emissions as waste.	The feasibility analysis should include the sensibility analysis of the system cost due to the uncertainties about resource and technology prices. - The solutions should be analysed as an alternative to biofuels; - The solution should be analysed within the existing framework and future governmental energy goals; - The solution should decrease the carbon emissions by recycling them into a valuable fuel product.

From the *financial resources* point of view the funds for transition to a 100% renewable system are in place through governmental funds, which covers all of the initiatives in the government's strategy for this transition. Moreover, on the European level there are funds for alternative fuels and transport technologies such as Horizon 2020 applications, which could be used for establishing the demonstration plant. The feasibility study must relate to the socio-economic and environmental impacts of the analysed technology. Under *natural and socioeconomic environment*, the main concerns are regarding the security of supply, to eliminate the dependency on oil, and how to reach the renewable energy goals set up by both the European Union and the Danish Government. From the transport perspective, these goals cannot be reached with the current strategy that suggests biofuels as the only renewable alternative to internal combustion engines; therefore, other alternatives should be analysed.

The different conditions presented have certain consequences on the feasibility study and what one should include. The feasibility study of electrofuels should analyse electrofuels as a possible alternative to biofuel. The production cycle of different fuel options should be assessed and the resources used in the production process should be outlined. The analysis should also include the assessment of the ability of electrofuels to integrate renewable resources and the cross-sector integration of these types of fuel pathways. The sensitivity analysis of the system cost will be conducted due to the uncertainties about resource and technology prices in the future. To complete the feasibility study under the presented criteria, it was decided that the energy system analysis tool be used in order to analyse the electrofuels as a radical technological change, how they incorporate the penetration of renewable energy in energy systems, and the long-term horizon, and to calculate the socio-economic perspective of this particular fuel type. Organisational and financial resources will not be analysed in detail; however, the discussion of the possibilities is included in the roadmap presented in Chapter 9.

4.2.1 Energy system analysis tool

The finalised electrofuel pathways will be investigated by using the energy system analysis tool EnergyPLAN. EnergyPLAN is designed under the Choice Awareness Theory and it enables analysis of energy systems with a high share of renewable energy sources [5]. It is freeware software that can be downloaded online at [128], and the model is accompanied by detailed documentation of the technologies, regulations, strategies, and the overall modelling sequences. The EnergyPLAN tool includes all sectors in the energy system: electricity, heat and transport. As was previously indicated, analysis of alternative options needs to be seen from the overall energy system point of view in order to find the best solution—EnergyPLAN is in line with this approach. This deterministic mathematical model can be used for three types of energy system analyses: technical simulation, market economic simulation, and feasibility study. Market economic simulation was not performed for electrofuels, as this mode of simulation cannot sufficiently represent how future energy supply and demand markets should be designed and, therefore, is better for short-term cost calculations of different energy supply technologies. EnergyPLAN optimises the technical operation of a whole system, which is very important from the socio-economic point of view as in the future the system will not be the same. Therefore, the technical simulation strategy and feasibility study were done as they better represent the systems with very large penetrations of renewable energy.

The model is based on an hourly approach for a one-year period, as opposed to the scenario models that analyse a series of years. This approach enables precise modelling of hourly fluctuations in demand and supply, as well as the influence of intermittency of renewable energy sources on the system. This is crucial when analysing 100% renewable energy systems and in order to determine whether renewable energy technologies meet the energy demands on the hourly basis. Another advantage of this tool is that it is developed on a research basis, meaning that it incorporates a number of new technologies, including electrofuels. EnergyPLAN also includes the balancing of the system in its system cost calculations, which is important because as electrofuels are produced with electrolysers that enable a high share of wind integration, the costs are more accurate when including balancing costs. EnergyPLAN was used both for the socio-economic cost analysis of the overall system and for the fuel production cost as a separate analysis.

4.3 DATA COLLECTION

To get to the stage of modelling the finalised pathways in the energy system analysis tool, it is important to know the individual stages of the production cycle of electrofuels and technologies implemented. The results of the technology analysis should be taken with a pinch of salt, as there are uncertainties in the data and the predictions for the future development of the technology. The data collection was mainly done through a literature review, as the interest was in the secondary data available that could be used to analyse this type of fuel as an integrated part of the energy system. The literature search included both scientific work from research papers and books, but also did not disregard the reports and online data in some cases. The literature review of relevant data was conducted not only at the beginning of the study, but also during the project, due to the novelty of the topic. The topic gained more interest somewhere in the middle of the research project; therefore, new data was incorporated. The expert group meeting and communication with many industrial representatives were sources of further knowledge for parts of the data that were not possible to find by the literature review.

4.4 PUBLIC REGULATION

According to Hvelplund and Lund [126] the changes in public regulation when implementing radical technological change should address four areas and this dissertation touched upon the technology development and the political perspective. The public regulation was not the main part of this dissertation, but the analysis of the historical development of the alternative fuel policies was included in order to create awareness of technologies that are promoted as renewable solutions. In addition, the implication of the existing policies on electrofuel development and deployment, as well as the roadmap for their integration, is presented and discussed. The reason why concrete recommendations for new public regulation were not presented concerns the many uncertainties when introducing new technologies with a long time frame, and suggesting new public regulation was not in the scope of the dissertation. The frame under which the public regulation in the dissertation was presented can be seen in Figure 5.

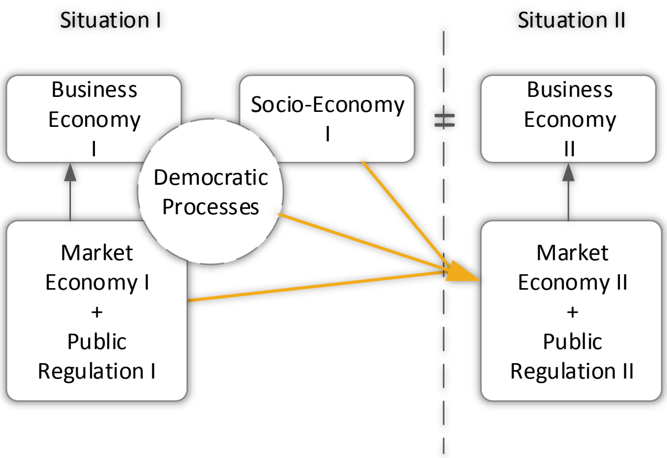

Figure 5. The relation between business economy, socio-economy, and public regulation (adapted from [126])

The focus was on the public regulation in place (related to renewable alternatives in transport) and the analysis of the socio-economy of electrofuels (Situation I). The socio-economic feasibility study conducted might show that the new technological development and investment are good from a societal point of view. If this is the case, then the initial roadmap (marked yellow in Figure 5) for the discussed technology is created in order to eventually develop and implement new public regulation that will ensure that what is best from the societal point of view should be the best from a business perspective. However, before the dedicated public regulation for electrofuels is to be created, there is a need for further development and demonstration of this technology.

5 PATHWAYS FOR FUEL PRODUCTION WITH BIOMASS CONSTRAINTS

As previously introduced, electrofuels are mainly renewable fuels produced by storing electricity as chemical energy in the form of liquid or gas fuels (see Figure 6). The production includes the combined use of electrolysers and a carbon source in order to store the electricity. As the topic of the dissertation is focused on 100% renewable energy systems, the electrofuels based on coal are disregarded. Therefore, the interest is in electrofuels using biomass or emissions as a carbon source. The aim of the fuel pathways is to minimise the use of biomass as it is a very valuable resource in 100% renewable systems and its potential is limited. The electrofuels based on CO_2 emissions are seen as a long-term solution that could help to eliminate the use of biomass in the transport sector. The end fuels can be varied as the production finishes with chemical synthesis that can produce different fuels based on the catalysts used. Even with the expected deployment of electricity for the private car fleet, the need for energy-dense fuel will be present for other modes of long-distance transport, such as trucks, buses, ships and aeroplanes. The use of electrofuels is prioritised for these types of transport modes.

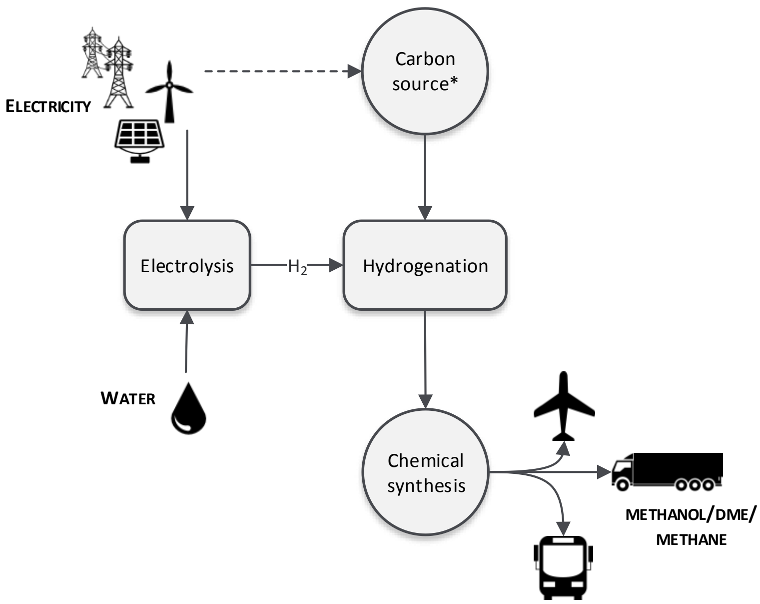

*Figure 6. Electrofuel production flow diagram for biomass hydrogenation and CO_2 hydrogenation pathways. *Carbon source is either biomass gasification or CO_2 emissions. Dotted line is used only in case of CO_2-based electrofuels.*

In the smart energy system concept, electrofuels enable cross-sectorial interaction, connecting the renewable electricity production with the transport sector and providing the balancing capacity in the system. This can be seen from Figure 7, where the conversion of excess electricity to fuel is highlighted.

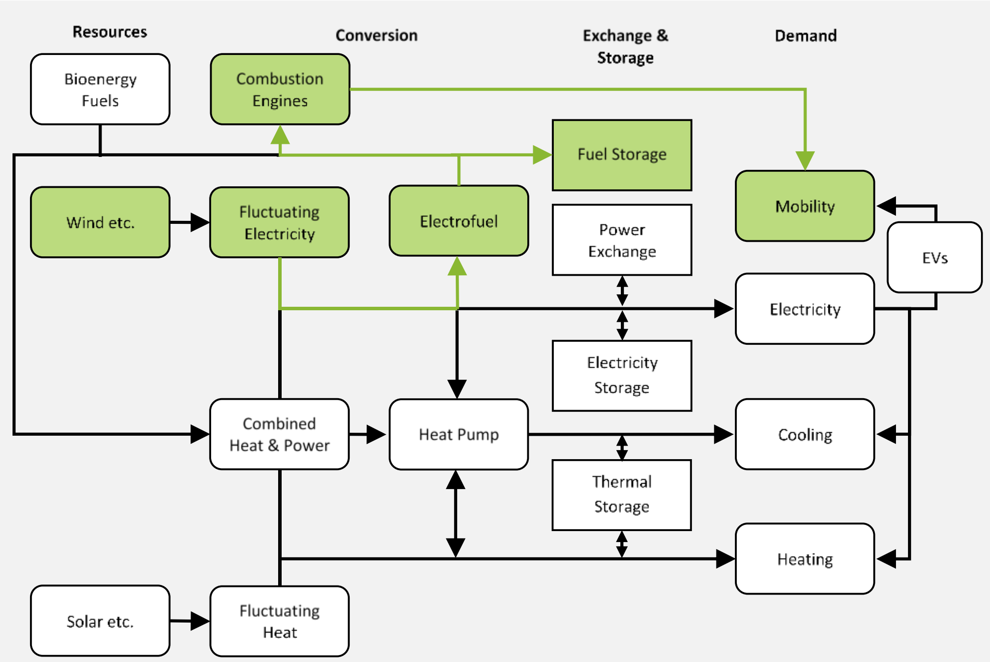

Figure 7. Interaction between sectors in smart energy systems. Highlighted boxes and lines indicate the conversion of fluctuating electricity into electrofuels for meeting the mobility demand or storing the fuel when not needed.

The high share of excess electricity is going to be one of the main characteristics of future energy systems, with the benefit of storing this electricity by producing fuels for transport being high. Electrofuels can also be stored in the fuel tanks and provide the same type of flexibility as current fossil fuels. The role of electrofuels in the systems is different from other types of fuels such as biofuels or synthetic fuels, as they integrate different energy system sectors and provide flexibility. The fuels of interest are methanol or DME as liquid options and methane as a gaseous option. The analysis included both liquid and gaseous options as it is not yet clear what fuel type will be used in the future for the transport sector, due to the uncertainties relating to vehicle efficiency, infrastructure cost, and future technological development. This, however, is not the key concern, nor should it be the decisive factor for adapting this production process, as the production cycle does not differ much and the output fuel can be adjusted when the factors on the demand side of the transport sector are clearer.

This chapter will present three fuel pathways that were analysed in this dissertation under the two fuel types: *CO_2 electrofuels* and *bioelectrofuels*. *Bioelectrofuels* are produced by biomass hydrogenation, while *CO_2 electrofuels* can be produced with two fuel production cycles: *CO_2 hydrogenation* and *co-electrolysis*. The main difference between electrofuel pathways is the source of carbon. The bioelectrofuels are produced by biomass gasification, and the produced gas is boosted with hydrogen from water electrolysis. CO_2 electrofuels are using carbon dioxide emissions as a carbon source. The emissions can be from stationary sources such as energy or industrial plants or in the future from air capturing. A description of each pathway (followed by a flow diagram) is given below.

It is important to note that methanol and DME are treated the same for the simplification of the calculations, which is possible due to the projected efficiencies of the vehicles used for these fuels. The losses of converting methanol to DME, with the dehydration process, are gained through higher efficiencies of vehicles fuelled by DME. Therefore, in the following text, methanol/DME (as a term) will be used when talking about the end fuel demand. The hydrogen needed in all pathways is provided by high-temperature electrolysis with SOEC. The electrolysers are powered by offshore wind turbines, and the electricity demand needed for fuel production is calculated from the ratio of hydrogen per fuel output and electrolyser efficiency.

5.1 BIOMASS HYDROGENATION PATHWAY

The main objective behind bioelectrofuels is to create biomass-based fuels by minimising the biomass input needed for the fuel production. This is done by boosting syngas produced by biomass gasification with hydrogen. The hydrogen is produced by steam electrolysis powered by renewable electricity, enabling the integration of fluctuating resources while, at the same time, lowering the biomass input. Depending on the fuel output, two flow charts including mass and energy balance are presented to show flows for methanol/DME (see Figure 8) and methane (see Figure 9). This production cycle integrates three energy sectors: power, heat and transport. Electricity from the power sector is converted to hydrogen, marginal heat from power plants is used for the gasification process, and the electrofuels produced are used in the transport sector. This is an example of how fuels for transport can play a part in the smart energy system.

The key step in bioelectrofuel production is the gasification of biomass. Different types of biomass can be used for gasification, such as wood or straw. Gasification of wood is already commercialised [129], while the gasification of straw is still on the demonstration scale [130]. For the analysis, gasification of cellulose was used and the mass and energy flows were calculated accordingly. The status of biomass gasification technologies is elaborated further in Chapter 6, and the review of the technology status in Denmark and Sweden was conducted in [122]. As illustrated in Figure 8 and Figure 9, after the biomass gasification, the produced gas is hydrogenated with hydrogen produced from electrolysis. In this step, the quality of syngas is improved, and the energy content is raised by using electricity to produce hydrogen. This step is crucial as it minimises the use of biomass needed for fuel production. The hydrogenated syngas is later converted with chemical synthesis to liquid fuels or methanated to produce methane.

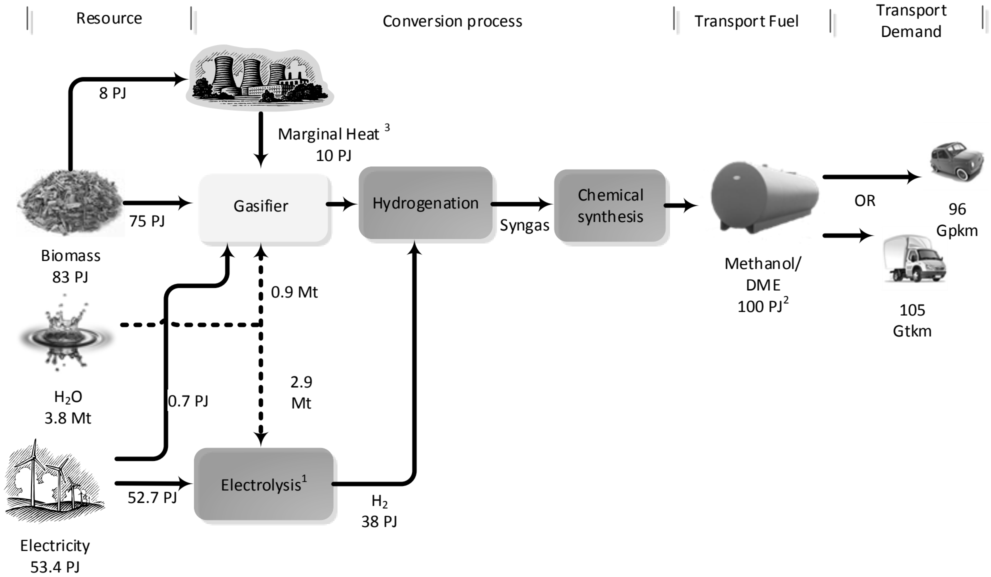

Figure 8. Methanol/DME production with steam gasification of biomass that is hydrogenated. [1] Assumed electrolyser efficiency is 73%. [2] Additional loss of 5% was applied to the fuel produced to account for chemical conversion and storing the fuel. [3] Assuming a marginal efficiency of 125% and a steam share of 13% relative to the biomass input.

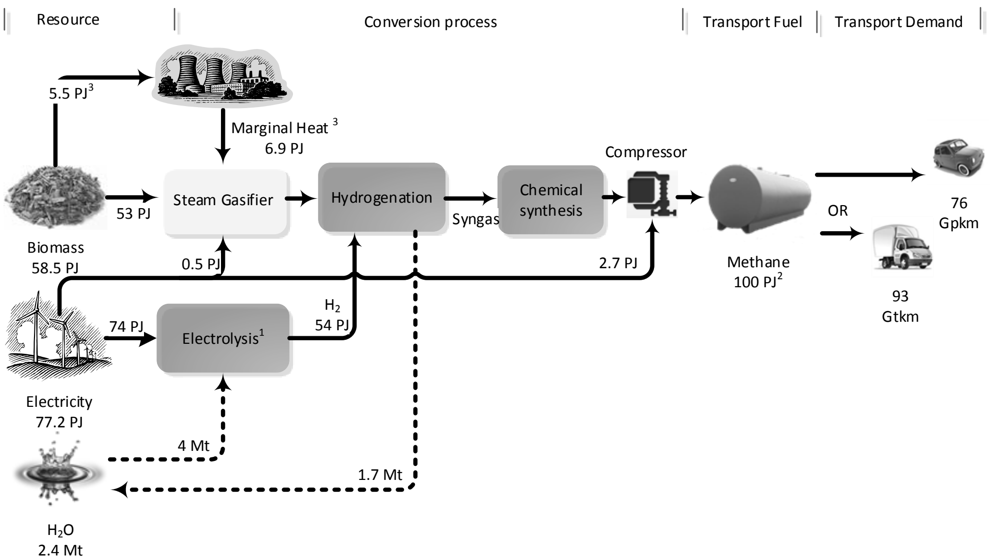

Figure 9. Methane production by steam gasification of biomass that is hydrogenated. [1] Assumed electrolyser efficiency is 73%. [2] Additional loss of 5% was applied to the fuel produced to account for chemical conversion and storing the fuel. [3] Assuming a marginal efficiency of 125% and a steam share of 13% relative to the biomass input.

The main differences between producing methanol/DME and methane lie in the additional energy for compression necessary for storing methane and the ratio of biomass and hydrogen. However, a difference is also in the vehicle driving range, which can be met by liquid or gaseous fuel. Methane enables a lower driving range, which is connected both with fuel properties and with the vehicle technology.

The mass and energy flows are based on equations (1) and (2). In practice, additional processes and losses would be occurring, but the overall energy flow can be taken as indicative if the process is going to be utilised in the future. It needs to be noted that the additional losses are included for both chemical synthesis and compression of methane.

$$\begin{array}{llllll} C_6(H_2O)_5 & + \ 6H_2 & + \ H_2O & \xrightarrow{Hydrogenation} & 6CH_3OH & \\ Biomass(Cellulous) & Hydrogen & Water & & Methanol & \\ 2823\ kJ & 1452\ kJ & 0\ kJ & & 3778\ kJ & (1) \\ 162\ g & 12\ g & 18\ g & & 192\ g & \end{array}$$

$$\begin{array}{llllll} C_6(H_2O)_5 & + \ 12H_2 & \xrightarrow{Hydrogenation} & 6CH_4 & + \ 5H_2O & \\ Biomass(Cellulous) & Hydrogen & & Methane & Water & \\ 2823\,kJ & 2904\,kJ & & 4800\,kJ & 0\,kJ & (2) \\ 162\,g & 24\,g & & 96\,g & 90\,g & \end{array}$$

In case the methane is used as a fuel in future systems, in order to use the gas network in place, it is possible to convert the methane to methanol if necessary. However, this is not recommended as the reforming of methane to methanol is a very energy-intensive process and the losses in this conversion can be up to 30% [131]. As the aim of the smart energy systems is to minimise the energy losses and provide high fuel efficiency, this process was not further analysed, but separate production facilities for producing either methanol/DME or methane are suggested.

For the fuel price calculations for bioelectrofuels (further details in Chapter 7), the following components are included: biomass gasifier, offshore wind turbines, electrolysers, and the synthesis plant.

5.2 CO_2 RECYCLING PATHWAYS

Carbon dioxide is a major polluter, and mitigation of harmful emissions is a great challenge. Instead of storing the captured carbon dioxide, it can be recycled by CCR into different products such as fuel and chemicals. The aim of CO_2 electrofuels is to provide fuels based on the recycling of carbon dioxide emissions and, in this way, offer a solution for mitigation or at least maintaining the levels of CO_2 emissions in the atmosphere. In order to produce fuel, carbon dioxide needs to be reacted with hydrogen that is provided from steam electrolysis by converting excess renewable electricity. This way of producing fuel not only enables the conversion of emissions to a valuable product, but also provides a strong interaction between energy sectors, which is important for future smart energy systems. Emissions can be recycled from CO_2-rich flue gases from stationary sources in heat and power sectors or from industry. In the future, it will be possible to recycle emissions from the atmosphere, despite the low concentration in the air of just 0.04% [132]. Capturing CO_2 from the atmosphere allows to capture emissions that are mostly related to human activities, and even to capture the accumulated atmospheric emissions. This would enable the stabilisation of CO_2 levels and with the current trend of emissions and temperature rising, this becomes a very valuable feature. In this dissertation, the calculations are made with the recycling of emissions from stationary sources for two reasons. Firstly, this is a more established technology; thus, cost predictions are more realistic. Secondly, according to the data from [43,133] the energy needed for capturing emissions from air is only 5% higher than in the case of recycling from stationary sources, but the price is significantly higher. Therefore, as the energy requirement for recycling of emissions is very similar, it was decided to use capturing from a stationary source as the price is cheaper. For the CO_2 electrofuel price calculations, the electricity demand needed for recycling CO_2 from a stationary source was calculated from the specified factors for electricity needed for extracting CO_2 (TWh/Mton) and extracted CO_2 per produced synthetic gas (Mton/TWh).

5.2.1 CO_2 hydrogenation

The CO_2 hydrogenation combines carbon dioxide from a stationary source with hydrogen from steam electrolysis to form syngas. Syngas can be further converted to methanol/DME or upgraded to methane. In addition, other fuel outputs can be created, but they are not part of this dissertation.

Three potential pathways are presented here:

- CO_2 hydrogenation to methanol/DME with CCR (see Figure 10)
- CO_2 hydrogenation to methanol/DME with air capturing (see Figure 11)
- CO_2 hydrogenation to methane with CCR (see Figure 12)

It is also possible to produce methane with air capturing of carbon dioxide (which can be seen in Appendix IV). As the analysis was made with stationary carbon dioxide capturing, no more details about the air capturing pathways are going to be presented here.

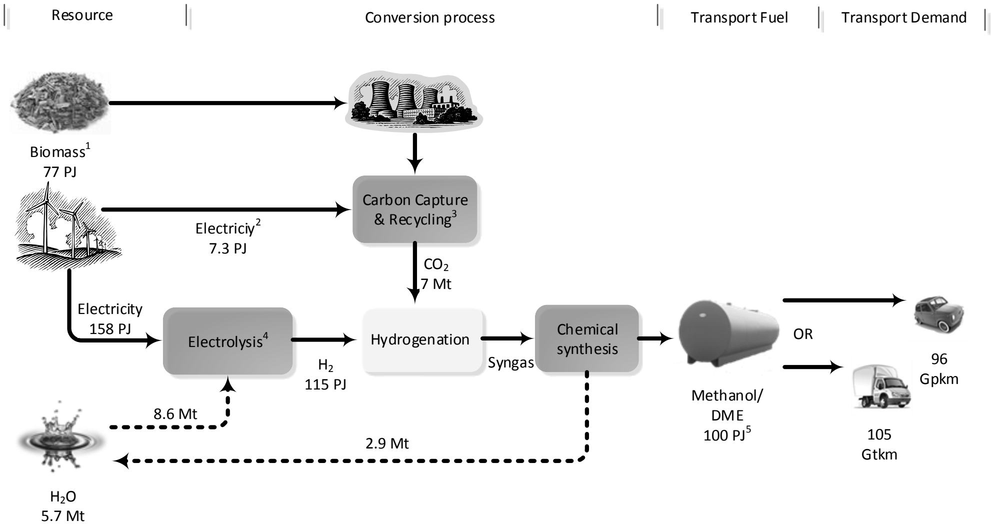

Figure 10. Hydrogenation of carbon dioxide using CCR to methanol/DME. [1]Based on dry willow biomass. [2]Based on an additional electricity demand of 0.29 MWh/tCO_2 for capturing carbon dioxide from coal power plants [134]. *[3]If carbon trees were used here, they would require approximately 5% more electricity* [133]. *[4]Assuming an electrolyser efficiency of 73% for the steam electrolysis* [40]. *[5]A loss of 5% was applied to the fuel produced to account for losses in the chemical synthesis and fuel storage.*

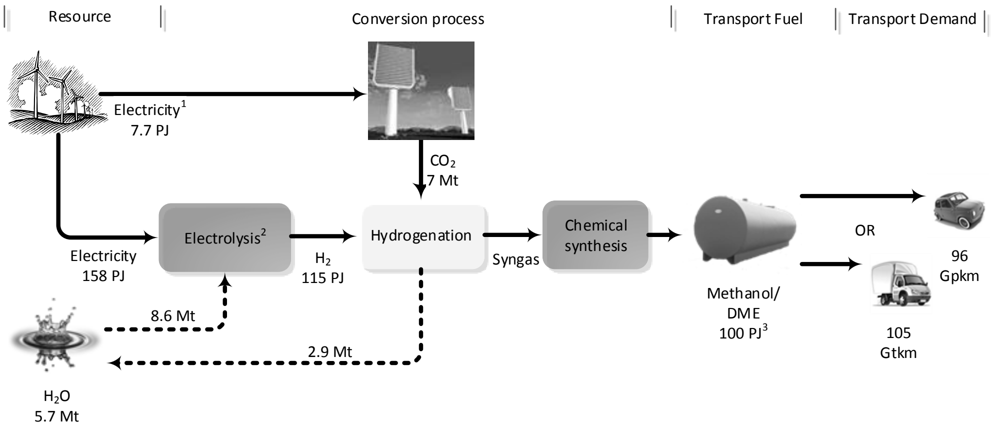

Figure 11. Hydrogenation of carbon dioxide sequestered using carbon trees to methanol. [1]Based on an additional electricity demand of 1.1 MJ/tCO_2 for capturing carbon dioxide using carbon trees [133]. *[2]Assuming an electrolyser efficiency of 73% for the steam electrolysis* [40]. *[3]A loss of 5% was applied to the fuel produced to account for losses in the chemical synthesis and fuel storage.*

As in the case of bioelectrofuels, the only difference between methanol/DME and methane is the carbon-to-hydrogen ratio (4) and the additional compressor (Figure 12).

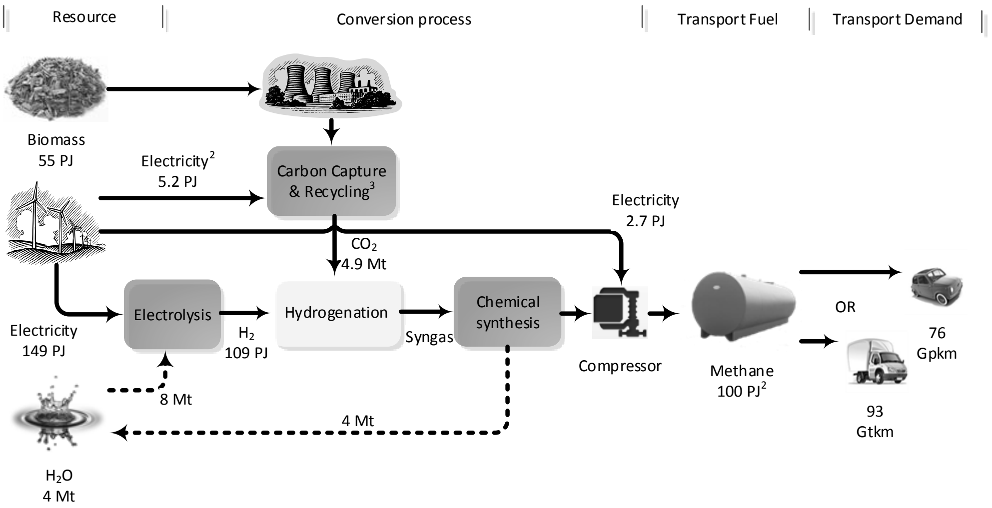

Figure 12. Hydrogenation of carbon dioxide using CCR to methane. [1]Based on dry willow biomass. [2]Based on an additional electricity demand of 0.29 MWh/tCO₂ for capturing carbon dioxide from coal power plants [134]. *[3]If carbon trees were used here, they would require approximately 5% more electricity* [133]. *[4]Assuming an electrolyser efficiency of 73% for the steam electrolysis* [40]. *[5]A loss of 5% was applied to the fuel produced to account for losses in the chemical synthesis and fuel storage.*

The mass and energy balances of chemical recycling of carbon dioxide with hydrogen are based on (3) and (4). Methanol synthesis is an exothermic reaction and it is important to control the process temperature to avoid deactivation of catalysts [44]. The methane synthesis is also an exothermic reaction, and calculated according to a Sabatier reaction (4).

$$\begin{array}{llll} CO_2 \quad + & 3H_2 \longrightarrow & CH_3OH + & H_2O \\ \textit{Carbon dioxide} & \textit{Hydrogen} & \textit{Methanol} & \textit{Water} \\ 0\ kJ & 726\ kJ & 630\ kJ & 0\ kJ \\ 44\ g & 6\ g & 32\ g & 18\ g \end{array} \tag{3}$$

$$\begin{array}{llll} CO_2 \quad + & 4H_2 \longrightarrow & CH_4 \ + & 2H_2O \\ \textit{Carbon dioxide} & \textit{Hydrogen} & \textit{Methane} & \textit{Water} \\ 0\ kJ & 968\ kJ & 800\ kJ & 0\ kJ \\ 44\ g & 8\ g & 16\ g & 36\ g \end{array} \tag{4}$$

5.2.2 Co-electrolysis

The co-electrolysis pathway has the same principle as the CO_2 hydrogenation pathway; however, it combines carbon dioxide and water in the same process (co-electrolysis), and produced syngas is later converted to a desired fuel. The produced syngas composition is different from the one in the previous pathway. Syngas has a 2:1 hydrogen-to-carbon monoxide ratio, which is a favourable ratio for further conversion to methanol. However, this should not be seen as an obstacle to convert the syngas to other types of fuels, as there are no barriers to do this conversion. The energy and mass balances are outlined in (5) and (6).

$$
\begin{array}{ccccccccc}
4H_2O & + & 2CO_2 & \xrightarrow{co-electrolysis} & 4H_2 & + & 2CO+(3O_2) & \longrightarrow & 2CH_3OH+(3O_2) \\
\textit{Water} & & \textit{Carbon dioxide} & & \textit{Hydrogen} & & \textit{Carbon monoxide} & & \textit{Methanol} \\
0\ kJ & & 0\ kJ & & 968\ kJ & & 566\ kJ & & 1259\ kJ \\
72\ g & & 88\ g & & 8.1\ g & & 56\ g & & 64\ g
\end{array}
\tag{5}
$$

$$
\begin{array}{cccccccccc}
3H_2O & + & CO_2 & \xrightarrow{co-electrolysis} & 3H_2 & + & CO+(2O_2) & \longrightarrow & CH_4 & +H_2O+(2O_2) \\
\text{Water} & & \textit{Carbon dioxide} & & \textit{Hydrogen} & & \textit{Carbon monoxide} & & \textit{Methane} & \textit{Water} \\
0\ kJ & & 0\ kJ & & 726\ kJ & & 283\ kJ & & 890\ kJ & 0\ kJ \\
54\ g & & 44\ g & & 6\ g & & 28\ g & & 16\ g & 18\ g
\end{array}
\tag{6}
$$

Using the stoichiometric approach simplifies the reaction that happens in reality, as there are actually many uncertainties in relation to how these reactions are taking place [135]. There are three reactions that are occurring behind the co-electrolysis process: electrolysis of water, electrolysis of carbon dioxide, and a reverse water gas shift reaction (RWGS). By using the stoichiometric approach, it is possible to preliminarily estimate the feasibility of this pathway.

As the output fuel analysed was both methanol/DME and methane, two potential pathways are presented here:

- Co-electrolysis to methanol/DME with CCR (see Figure 13)
- Co-electrolysis to methane with CCR (see Figure 14)

Corresponding to the CO_2 hydrogenation pathway, methanol/DME and methane production with air capturing is possible and the flowcharts can be seen in Appendix IV. In comparison to CO_2 hydrogenation, the water input is lower for co-electrolysis, but the net water requirement for hydrogen production is the same. Overall, CO_2 hydrogenation and co-electrolysis have the same electricity requirement for carbon extraction and electrolysis. However, the steam electrolysis used for the first pathway is already a well-established technology, while the co-electrolysis is still under research and development [135]. This could be a deciding factor when choosing between these two production pathways, but currently it cannot be foreseen which one will be preferred in the future.

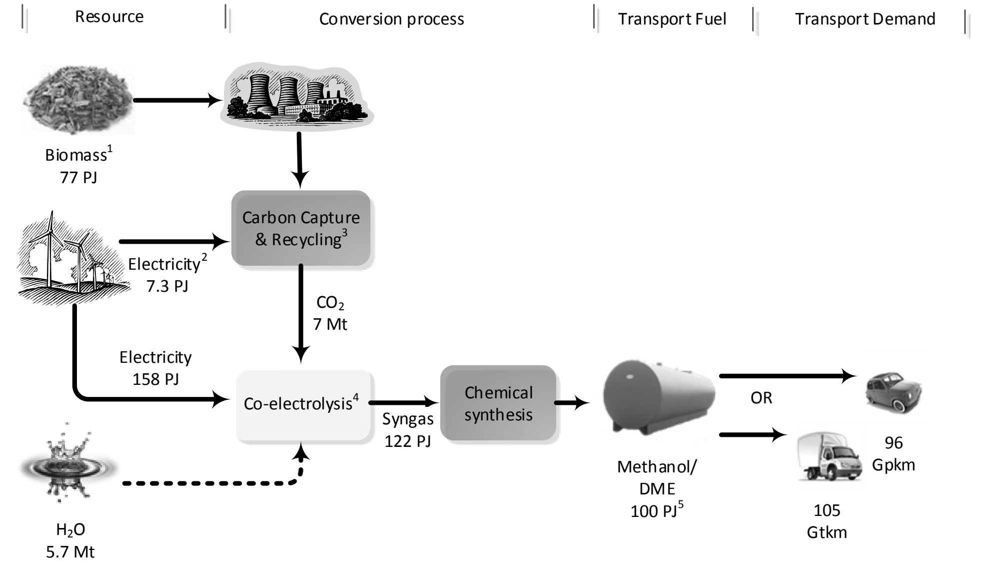

Figure 13. Co-electrolysis of steam and carbon dioxide obtained using CCR to methanol/DME. [1]Based on dry willow biomass. [2]Based on an additional electricity demand of 0.29 MWh/tCO$_2$ for capturing carbon dioxide from coal power plants [134]. *[3]If carbon trees were used here, they would require approximately 5% more electricity* [133]. *[4]Assuming a co-electrolyser efficiency of 78%: 73% for steam and 86% for carbon dioxide* [40]. *[5]A loss of 5% was applied to the fuel produced to account for losses in the chemical synthesis and fuel storage.*

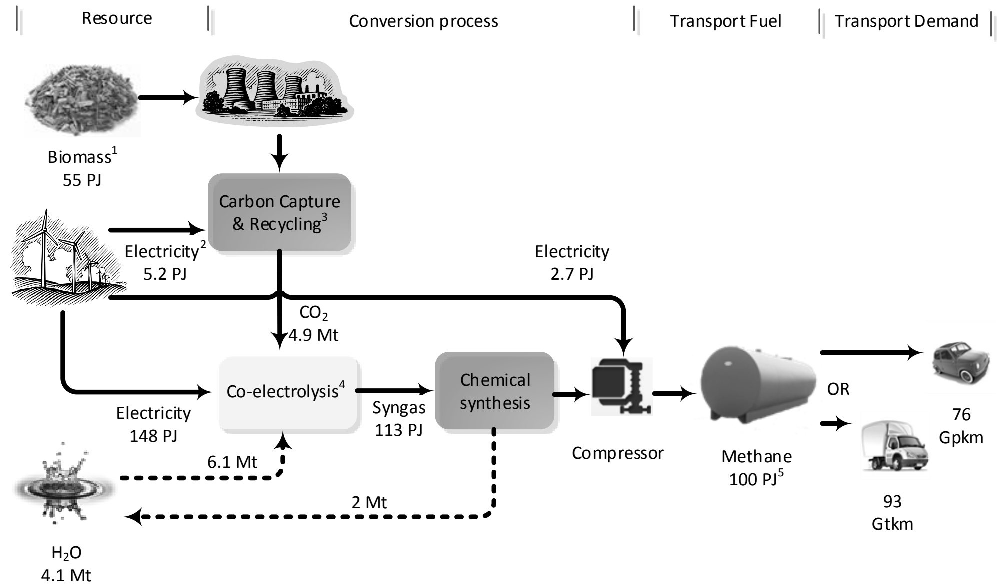

Figure 14. Co-electrolysis of steam and carbon dioxide obtained using CCR to methane. [1]Based on dry willow biomass. [2]Based on an additional electricity demand of 0.29 MWh/tCO$_2$ for capturing carbon dioxide from coal power plants [134]. *If carbon trees were used here, they would require approximately 5% more electricity* [133]. *[4]Assuming a co-electrolyser efficiency of 78%: 73% for steam and 86% for carbon dioxide* [40]. *[5]A loss of 5% was applied to the fuel produced to account for losses in the chemical synthesis and fuel storage.*

6 SYSTEM ARCHITECTURE ELEMENTS FOR UTILISING ELECTROFUELS

The chapter begins with an overview of the individual stages of the electrofuel production cycle, the main characteristics of technologies used, and their current development status. Furthermore, the integration of electrofuels in relation to the present infrastructure situation is described, including the current vehicle trends, fuelling infrastructure for proposed electrofuels, and the fuel properties and safety. The chapter finishes with a short overview of the infrastructure requirements and system design.

6.1 TECHNOLOGIES IN THE PRODUCTION CYCLE

As the pathways were presented in the previous chapter, this chapter goes into detail about each individual technology that is important for electrofuel production. The production cycle of electrofuels – both bioelectrofuels and CO_2 electrofuels – can be divided into six main steps (see Figure 15). The literature review of six steps is given below.

1. Energy source

- Electricity for powering the production cycle

2. Carbon source

- CO_2 emissions from stationary sources or air capturing
- Biomass gasification

3. CO_2 transportation and storage

- Possibilities of transporting CO_2 at longer distances in order to explore solutions for infrastructure options

4. Electrolysis

- Water/steam electrolysis or co-electrolysis

5. Syngas transportation and storage

- Possibilities of syngas transportation and storing instead of direct conversion to fuel

6. Fuel synthesis

- Catalytical synthesis to one fuel output

Figure 15. The main production steps of electrofuels

6.1.1 Energy source

The energy source is related to the electricity supply for electrolysers in order to produce hydrogen from water electrolysis or for the co-electrolysis process. As the idea behind electrofuels is to store the electricity, in a 100% renewable energy system the need for storing electricity is mostly when the excess electricity is produced in the system. This excess electricity comes from fluctuating renewable resources such as wind or sun. In the analysis, offshore wind was used for powering electrolysers, as according to the created 100% renewable energy scenario for Denmark [89], wind power is the biggest electricity supplier. Offshore wind technology is a developed technology already deployed in the Danish energy system.

6.1.2 Carbon source

Bioelectrofuels obtain their carbon source from *gasification of biomass*, while CO_2 electrofuels can *recycle carbon dioxide emissions* either from stationary energy or industry-related sources or by air capturing. Both carbon sources are described further in the subsections below. Gasification of biomass is an emerging technology, but has its development roots 180 years ago. The carbon capture from stationary sources is also a widely investigated technology, even though it is not utilised on a large scale. While the idea of the air capturing technology dates back to the 1940s [136], technology has gained more interest in the last 15 years [43,133,137–142] and it is seen mostly as a future technology.

The carbon obtained from biomass gasification is connected to the bioenergy potential that can be used in specific cases. Detailed analysis of bioenergy potential in Denmark was conducted in [89], including three different scenarios: business-as-usual, conversion to organic farming, and changing dietary habits. The bioenergy potential used in this dissertation is aligned with the 2050 target used in CEESA of 240 PJ/year [89].

6.1.2.1 Recycling of carbon dioxide emissions

In order to produce CO_2 electrofuels it is necessary to recycle carbon dioxide emissions, and currently this can possibly be done by capturing it from CO_2-rich flue gases from industrial or energy-related production sites. This can be done by physical-chemical absorption and desorption cycle followed by chemical purification of pollutants when necessary [44]. The emissions produced only by energy use in EU 28 in 2012 that could be captured with this technology comprised 3,438 million tonnes/year according to Eurostat [143]. As CO_2 hydrogenation requires 7 million tonnes to produce 100 PJ of methanol/DME, this implies that the emitted emissions in Europe, if recycled for fuel production, can cover demand higher than the present demand in the transport sector. In 2006, Denmark inaugurated the first pilot plant for the capture of carbon dioxide at Elsam Kraft A/S Esbjerg as part of the CASTOR project, with four test campaigns being conducted in the period from 2006 to 2007 [144]. This was an initiative to consolidate Europe's position in this field. Finkenrath [145] reported a cost overview of capturing and compressing the carbon dioxide from power generation by different technologies. He also lists the penalty losses that result in a reduction of electricity generation efficiency if the carbon capturing is installed at the plant, ranging from 7–10%, depending on whether it is a natural gas or coal power plant. In [146] the authors give an overview of capturing costs for different types of plants. The costs for carbon capturing and recycling used for the analysis are adapted from [147] and represent a cost prediction for 2050. The costs were for post-combustion capturing as it is the most developed one and removes the carbon dioxide from the flue gases. This process uses a chemical sorbent that can be recycled when the CO_2 is released for compression [148].

Many individual emitters are contributing to global warming by emitting GHG emissions, such as different transportation means and households. These emissions cannot be captured by previously introduced technology as the CO_2 concentration is lower or the emitters are in motion. These emissions can be tackled by air capturing, which enables capturing even the accumulated emissions from the atmosphere. Lackner *et al.* [43] reported a recent overview of the technology status, indicating the price for air capturing. This method at the current stage of development is more expensive than CCR, but from a technical perspective, it just requires approximately 5% more energy for extraction of carbon dioxide [133]. This is not significant from a system perspective; therefore, the costs and the maturity of the technology are the determining factors for the technology choice. The air capturing seems to be technologically feasible [137], but the economical perspective is expected to be improved with further research and development. Using air capturing for electrofuel production would enable a closed carbon loop, providing carbon-neutral fuel, which is a desired possibility for the climate mitigation.

In the current energy system, where the fossil fuels are providing the majority of our energy needs, the lack of carbon is inconceivable. However, when talking about future renewable systems where the only reliable carbon source is biomass and biomass-related emissions from the heat and power sectors or industry, there is a possibility of a CO_2 bottleneck. This certainly is an extreme situation, if the air capturing is not a possibility. The calculations for Denmark 2050 confirm that there will be enough CO_2 emissions from the stationary sources which can be utilised for fuel production [89]. As this may not be an option in other energy systems, the air capturing could potentially become an important technology for producing electrofuels.

6.1.2.2 Biomass gasification

Compared to coal gasification, which is the globally deployed technology, biomass gasification has become commercially available in the last 5 years. Few countries have been in front of biomass gasification by demonstrating and commercialising the technology [54,129,149–151]. Still, most of the existing biomass gasifiers installed are used for heat generation and their use for syngas production is still minor.

Kirkels and Verbong [152] presented a historical overview of the biomass gasification technology in the last 30 years, concluding that the technology still has limited niche development. Biomass gasification usually operates at lower temperatures than traditional coal gasification (500 to 1400°C, depending on the type of gasifier) and it converts any carbonaceous biomass to a combustible gas mixture [153]. By using different gasification agents, the biomass quality and value are upgraded into gaseous fuels [154]. Some types of biomass need to be pre-treated before the gasification process, which is important as the quality of the biomass input has an influence on the thermal efficiency of the process [155] and the fuel properties [156]. By using different types of gasifiers and operating temperatures [157], a different quality of gas products can be obtained depending on the purpose of its further use. The transport fuel production requires high-quality syngas without nitrogen, compared to low requirements for heat and power production. In his analysis, Ptasinski [158] compared gasification efficiency depending on the different biomass inputs, showing that the highest efficiency can be achieved for a straw and wood biomass.

There were five biomass gasification plants with production capacities bigger than 50 MW_{fuel} installed in 2012, and four planned or under-construction projects with higher capacities than 50 MW_{fuel} at that point [159]. A full list of gasification facilities worldwide, including the map of the facilities, can be found in the World Gasification Database [160]. With the commercialised wood gasification on a large scale [129] and the straw and energy crops gasification in a demonstration phase [130,161], biomass gasification is held as a promising technology for future energy systems. The review of biomass gasification in Denmark and Sweden [122] has shown that Sweden can be seen as a leader in biomass gasification technology for fuel production. Sweden has research in three different types of technology—direct gasification, indirect gasification, and suspension gasification—supported by the Swedish Gasification Centre [162]; apart from the strong focus on fuel production from biomass gasification, the development is also for the heat and power sectors. The first commercial biomass gasification-to-fuel plant, converting forest biomass to methanol, will be opened in Sweden [55]. Denmark, on the other hand, has a primary goal to use biomass gasification in combined heat and power facilities in order to replace coal district heating plants. The two best examples from Denmark of deploying biomass technology are the gasifiers in Skive and Harboøre [163]. Skive was the first commercial-scale bubbling fluidised bed gasifier, and is used to generate power and heat for district heating [164]. Harboøre is the oldest biomass gasifier in Denmark, operating since 1993. The last 12 years have been operated in CHP mode [165]. However, the interest is slowly redirected towards a wider spectrum of applications, including fuel production, using gasifiers as a balancing agent in the system and a combined use of gasifiers and fuel cells [149]. Denmark has recently closed its Pyroneer gasifier [166], which was a 6 MW_{th} demonstration plant fired with straw, manure fibres or local residues, despite the previously planned expansion to 50 MW [161]. Pyroneer was a low-temperature circulating fluidised bed gasifier that could use difficult and low-value fuels. Together with the development of two stages, Pyroneer enabled Denmark to be internationally recognised as a biomass gasification expert.

6.1.3 CO_2 transportation and storage

Transportation of carbon dioxide can play an important role when designing the infrastructure for electrofuel production. If the costs are not too high, then the opportunity is to build the production facility further from the carbon source. The flexibility can also be accomplished by short-term carbon dioxide storage and using it when needed, avoiding direct use after capturing. As the carbon capture and storage gained a lot of interest in the climate mitigation discussion, the transportation of CO_2 is reported in the literature in relation to it [167–169]. The USA is the country with the highest deployment of carbon dioxide transportation, as it is used for oil recovery and the existing pipeline network in place is almost 6,000 km long [170]. As the transportation of carbon dioxide in the gaseous phase is rather inefficient, most of the pipelines are transporting it as a supercritical fluid [168]. There is an option to transport gas in its liquid phase after compression and cooling, which would offer a less cost-intensive solution [171].

In his review, Roddy [172] highlights that the costs of carbon dioxide transportation are still not transparent enough. McCoy *et al.* [173] and Svensson *et al.* [168] gave an overview of carbon dioxide transportation costs. McCoy *et al.* [173] developed a pipeline cost model for the USA, with results ranging from €0.11/tonne of CO_2 for a 10km pipeline to €3/tonne of CO_2 for a 200km pipeline. Svensson *et al.* [168] show that the transportation costs with pipeline and water carriers are the lowest. According to [174] the transport costs for a pipeline can oscillate significantly, depending on the length of the pipeline and the volume transported. Carbon dioxide can be stored for short periods in the compressed tanks by using the same technology as compression of natural gas. According to [175], 119 kWh of electricity is needed for compression per tonne of CO_2. Based on the different energy costs and needed pressure, the compression cost can vary between €1.1 and €1.5/tCO_2 [176]. The summary of the costs is given in Table 2.

Table 2. Costs for carbon dioxide capture & recycling and transportation

	Types of costs	Unit	Low	High	Average	Ref.
CO_2 capture and recycling	Specific investment costs	M€/MW	1.8	3.2	2.7	[147]
	Recycling costs	€/t CO_2	-	-	30	[147]
Air CO_2 capturing	Recycling costs	€/t CO_2	28	930	493	[43]
CO_2 transportation	Transport costs for onshore pipeline[2]	€/tCO_2	-	-	5.4	[174]
	Transport costs for onshore pipeline[3]	€/tCO_2	1.5 (for 180 km)	5.3 (for 750 km)	3.5	[174]

[2] Transported volume of 2.5 Mtpa in connection with the carbon source
[3] Cost estimates for large-scale networks of 20 Mtpa

6.1.4 Electrolyser technology

Based on the electrolyte used, potential electrolysers for electrofuel production are divided into *alkaline electrolysers* using a liquid electrolyte, while the *polymer membrane (PEM)* and *solid oxide electrolysers cell (SOEC)* use a solid electrolyte. The operating temperatures of alkaline and PEM electrolysers are lower than SOEC, even when considering high-temperature alkaline and PEM. A growing body of literature has investigated H_2O electrolysis [31–33,177,178]. A recent review of literature on high-temperature electrolysis [36] compared different types of electrolysers and their performance.

Alkaline electrolysers have been available for more than 100 years; they are mostly used for industrial purposes and they are the most established electrolysis technology. Alkaline electrolysers can operate at atmospheric pressure or pressurised, making their response time very fast [179]. The operation temperature goes up to 90°C, but there are experimental concepts that can reach temperatures of 400°C [180]. There is, though, very limited availability of experimental data on alkaline electrolysis above 150°C, but it is proven that increasing the operating temperature increases the electrolysis performance [36]. Depending on their production capacity and operating pressure, the efficiency can be in the range of 38–70% (LHV) [180]. The largest realised alkaline project is 160 MW, which was constructed in the 1960s in Egypt [181].

PEM electrolysers are commercially available, even though their capacities are still limited. The operation temperature of PEM electrolysis is similar to alkaline (50–80°C) [51], but it was experimented in the 1990s with an operation temperature of 200°C [182]. The efficiencies of PEM electrolysers reported in the literature have significant variations from 48 to 72% [32,180,183,184]. The lifetime of PEM electrolysers is limited, due to the nature of the membrane, and it is below 20,000 h according to [181]. It is expected that the lifetime of the cell is going to be prolonged, but the expectations of the extent are different [181,183]. Materials for PEM electrolysers are very expensive; therefore, this technology is much less attractive from an economic point of view. The largest planned PEM electrolyser installation for hydrogen production is 20 MW [185]; moreover, for the MefCO2 project in Germany, which will generate methanol, using CO_2 and renewable electricity, a 1 MW PEM electrolyser will be installed [186].

As both PEM and alkaline have lower efficiency than SOEC, and as they can only be used for water electrolysis, the SOEC is an attractive solution for future energy systems. The SOECs, compared to alkaline and PEM electrolysers, are capable of electrolysing carbon dioxide and conducting a combined H_2O and CO_2 electrolysis known as the co-electrolysis process. The overall reaction pathway of co-electrolysis is not clearly defined [135], but there are significant advantages of co-electrolysis operation, such as higher efficiency [40] and the direct production of syngas. Recently, there has been a breakthrough in CO_2 electrolysis in molten carbonate cells [36], which disproves the belief that only SOECs are capable of electrolysing carbon dioxide. SOECs have been mostly tested and developed in laboratory surroundings and the commercial breakthrough is still to come. At the end of 2014, the project by German company sunfire GmbH for liquid fuel production was inaugurated and the SOEC capacity was installed in order to produce hydrogen for reacting with carbon dioxide [37]. According to Ebbesen *et al.* [36], SOECs suffer from high degradation rates, which is the main problem as the durability of the cell is still to be addressed. According to Laguna-Bercero [35], SOECs are a very promising technology, with high operating efficiency and fast kinetics. The efficiency can be even further increased through pressurising the cells [38]. It appears that the durability issue is the biggest challenge for successfully operating and deploying SOEC in the energy system [187].

The data used for analysis in terms of efficiency and performance of electrolysers is presented in Table 3, and the costs in Table 4. Data is adapted from Mathiesen *et al.* [40].

Table 3. Technology data for alkaline and SOEC, state-of-the-art (2012), and assumed development for 2020–2050

		Alkaline electrolysers		***SOEC***		
Production of		**H_2**		**H_2**	**CO**	**Syngas**
Available from		**2012[6]**	**2020–2030[4]**	**2020–2050**		
Capacity for one unit	*MW*	3.4[5,6]	>3.4	0.5–50		
Output	*Bar*	<30	4–30	40		
Operating temp.	*°C*	60–80	60–90	800		
System efficiency	*% (LHV)*	67	50–70	76.8	90.3	81
Electricity to heat efficiency[7]	*% (LHV)*	5	5	5	5	-
Other input		Ambient air, water	Ambient air, water	Steam	Pure CO_2	Steam and pure CO_2
Start-up time	*Hours*	Depends on the system, can have rapid response		0.2[8]		
Regulation ability						
Fast reserves	*MW per 15 min.*	Full capacity	Full capacity (in 10 min.)	Full capacity		
Regulation speed	*% per second*	0.001	0.004	3 down / 0.1 up		
Minimum load	*% of full load*	10–20	10–20	3		

[4] The alkaline and PEM electrolyser data are modified from [183] and [181].
[5] The largest alkaline electrolyser plant in operation is 160 MW, with an average module size of 1.2 MW [181].
[6] Represents a large alkaline electrolyser with a pressure of 30 bar, and capacity of 500 Nm^3/h. The electrolyser is turned off only for maintenance purposes and, therefore, has a load factor of 98%.
[7] There are no empirical data on available waste heat that can be utilised for district heating purposes.
[8] The start-up time is several hours if started from cold.

Table 4. Cost data for alkaline and SOEC (2012 prices)

		Alkaline		SOEC		
		2012	**2020–2030**	**2020**	**2030**	**2050**
Investment costs	*M€/MW*	1.07[9]	0.87[9,10]	0.93[11]	0.35[10]	0.28[10]
Fixed O&M costs	*% of inv./year*	4	4	3	3	3
Variable O&M costs	*€/MWh*	-	-	-	-	-
Lifetime stack	*h*		<90,000	<90,000	<90,000	<90,000
Lifetime system	*Years*	20–30	25–30	10–20	10–20	10–20

6.1.5 Syngas transportation and storage

As for the CO_2 transportation and storage, the cost-effectiveness of syngas transportation and storage can influence the outline of the production facility. Synthetic gas or, shortly, syngas should not be mistaken for synthetic natural gas, as the latter can be transported in the existing natural gas network. Syngas cannot be transported through a natural gas network as it contains a high percentage of hydrogen and the gas has explosive potential. The general accepted use of the term *syngas* refers to a 2:1 mixture of H_2 and CO [188], but it can contain carbon dioxide, methane, and smaller impurities such as chlorides, sulphur compounds, and heavier hydrocarbons [189]. Throughout this dissertation the term *syngas* is used both for the mixture of CO and H_2 (used in co-electrolysis pathways) and for the mixture of CO_2 and H_2 (used in CO_2 hydrogenation pathways). The transportation of syngas is more complicated than the transportation of carbon dioxide, due to the component properties. The hydrogen causes leaking problems and burns with invisible flames; therefore, the possibility of injuries is higher in case of an accident. The toxicity of carbon monoxide is very high, and creates an explosive gas when mixed with hydrogen. In order to transport syngas it is necessary to build a new gas network that can accommodate the safety requirements and the gas properties.

Few studies have been published on syngas transportation as most of the studies focus more on hydrogen transport via a natural gas pipeline. The natural gas pipeline can handle up to a maximum of 20% hydrogen, but with concentrations below 15%, very few modifications are necessary [190]. The Danish Gas Technology Centre (DGC), GreenHydrogen, Energinet, and DONG are conducting a long-term project on the stability of a natural gas pipeline with different concentrations of hydrogen up to 20% [191]. The most detailed identified publication available is by the European Industrial

[9] Including costs associated with grid connection (66,000 €/MW for large plants).
[10] Cost for large alkaline pressure electrolyser with a capacity of 1500 Nm^3/h
[11] Average cost for period of 2030–2050, including improvements in grid connection, of €66,000/MW for large plants

Gases Association [189] and it is a manual for constructing syngas and other carbon dioxide mixture pipelines. The lack of literature is rather unusual, as before the 1970s the gas transported in the gas network was a mixture of hydrogen, carbon monoxide and methane, which is similar to the syngas mixture [192]. Herder reports [193] potential options for syngas transport, suggesting a double bus network for two different qualities of syngas. It is also possible to tune the syngas mixture to avoid the self-ignition problem of CO [194].

6.1.6 Fuel synthesis

Syngas can be converted to many different fuel outputs depending on the end-use need. The most known synthesis process for converting syngas to a valuable fuel product is Fischer–Tropsch (F–T) synthesis. There is a vast amount of literature on Fischer–Tropsch, as it dates from the mid-1920s [195]. Fischer–Tropsch synthesis is used for xTL processes coal-to-liquid (CTL), gas-to-liquid (GTL) and biomass-to-liquid (BTL) for producing liquid synthetic fuels [196]. Van de Loosdrecht [197] gives a detailed summary of Fischer–Tropsch synthesis, from its historical development to the particulars on different catalysts and the process reactions. Depending on the desired product from the synthesis, petrol or diesel, low- or high-temperature reactors need to be used [198]. F–T synthesis produces a chain of hydrocarbons, with the distributions of products being defined by the function of chain growth [199].

As the fuel outputs of interest are methanol/DME or methane, the direct synthesis into these products is used. Fischer–Tropsch was also not considered from an efficiency point of view as the chained products that accompany the main fuel output are lowering the efficiency of the process. There are many commercial producers of methanol plants, mostly differing in the catalysts used for the process [123,200,201]. DME can be produced by methanol dehydration or in a single-stage process directly from syngas [202]. One of the biggest developers of DME synthesis is Danish company Haldor Topsøe. Fleisch *et al.* [203] have reported on the thermal efficiency of single-stage DME production ranging from 59 to 68% (LHV). The conversion of carbon dioxide to methanol and DME with hydrogen has gained more interest in recent years [204,205]. In their recent review on catalyst technologies, Ali *et al.* [206] included an overview of methanol synthesis from CO_2 hydrogenation and from syngas. The cost assumption for methanol/DME synthesis is for methanol synthesis from syngas in a pressurised catalytic process [183].

For methane production, a well-established methanation process can be used [207]. In his report for the Danish Gas Center, Rasmussen [208] gives an overview of the most successful methanation technologies used in practice. In cases of producing methane, the preferable pathway would be biomass hydrogenation, as it involves a gasification process. The gasification process favours methane formation if the pressure conditions are increased [209]. Burkhardt and Busch [210] present a new method for methanating carbon dioxide and hydrogen, which could be relevant for CO_2 hydrogenation pathways. Long *et al.* [211] presented a novel single tubular design for direct synthesis of methane from co-electrolysis, demonstrating excellent integration of SOEC co-electrolysis and an F–T reactor for methanation.

6.2 FUEL PROPERTIES AND HANDLING

The overview of the fuel properties of methanol, DME and methane is given below, including some details on their influence on human health and the environment, handling issues, and engine performance. The summary of the main properties is outlined in Table 5 at the end of the section.

Methanol is widely used as a raw material in the chemical industry for production of chemicals such as formaldehyde and acetic acid [212]. Many of the chemicals produced from methanol are used for daily products such as windshield washer fluid, plastics, pigments, and insulation. Methanol is a colourless, odourless liquid that is dissolvable in water and many other organic solvents. Methanol burns slowly and it has a high octane rating, so it is inherently safer than petrol in terms of fire safety, as the concentration in air has to be four times higher than for petrol to be ignited. The main characteristics of its flammability are the flash point of 12.2°C (petrol -43°C), which puts methanol in a category safer than petrol, and the ignition temperature of 470°C (petrol 246–280°C). However, methanol burns with invisible flames, so it can present a problem for firefighters when putting out the fire [213]. The most used argument against the use of methanol is its toxicity and danger of leaking in the water. Methanol is highly toxic only when ingested in larger amounts, and can cause metabolic acidosis, blindness, and even death. Details on methanol as a fuel, its properties, toxicity, and human and environmental safety were published in [214]. According to safety guidelines for methanol by NFPA [215], the safety results are the same as for petrol. Methanol is dissolvable in water, which can potentially cause issues if there is a leak in the water system. However, it has a high rate of biodegradation and a low bioaccumulation factor, meaning that only in situations where the concentrations in water exceed 10,000 mg/l is there a danger of effects on the microbial population [214]. According to Chinese experience of using methanol, no health problems were reported within workers or users regarding hundreds of millions of refuelling on their stations [216]. The Shanxi province, as one of the biggest deployers of methanol in China, has reported a reduction in emissions of CO, NOx and benzene of 20%, and reductions in particulate matter of 70% [217]. Methanol has excellent combustion characteristics, making it a great replacement for internal combustion engines (ICE). It has a high octane rating of 100, but its energy density is low compared to petrol. When it comes to using methanol in ICE, alteration of the engine is necessary as methanol has a corrosive character towards some metals, particularly aluminium, which was until recently used as a preferential material along with cast iron for engine blocks. A recent presentation by Bromberg [218] stated that methanol properties enable high-efficiency engines, increasing the efficiency of a standard petrol engine by 50% and a diesel engine in trucks by 20–25%. Vancoillie *et al.* [219,220] have analysed the use of methanol in dedicated engines and also in flexi-fuel vehicles, demonstrating that methanol can improve the engine performance and have efficiencies up to 42%, similar to diesel engines.

Dimethyl ether (DME), as the simplest ether, has similar properties to liquefied petroleum gas (LPG), being transported as liquid and stored in low-pressure tanks [44]. DME is colourless, nontoxic, noncorrosive, noncarcinogenic and volatile, with a minimal environmental impact [97]. DME has a boiling point of -23.6°C, a flash point of -41°C, and an ignition temperature of 350°C. Compared to methanol and methane, DME is not odourless, but has a sweet ether odour. DME has a very high cetane number above 55, which is higher than for diesel. This is the most important characteristic of DME, as it can be used as a substitute for diesel in compression ignition engines. The exhaust emissions from DME have no particulates, CO, NO_x, and no sulphur products, so it can be seen as a preferred option to diesel when it comes to the tailpipe side. DME as a fuel is good for a cold start as the vehicle can start even with the temperature as low as -24°C. On the other hand, DME has a low viscosity and it needs a lubricant improver to ensure normal service to the injection system. McCandless and Shurong in their paper from 1997 state that it is impossible to use DME in existing diesel engines due to the internal system leakage and inappropriate injection pumping rates [221]. Their claim seems to be somewhat exaggerated as Volvo engines can be adapted to DME by modification of the tank system, injection system, and engine management [222]. In their review, Arcoumanis *et al.* [96] list the requirements for fuel injection systems for DME, stating that there is a need for lubricity additives and anti-corrosive sealing materials to secure leakage-free operation.

Methane is a non-toxic gas and is lighter than air. It has no odour and it is noncorrosive. Methane is much safer than petrol and diesel as it has a limited range of flammability. Methane has a very high octane number of around 130, which is much higher than petrol, making it good for spark ignition engines. It produces approximately 25% less carbon dioxide emissions than petrol or diesel due to the lower carbon content of the fuel. It is easy to ignite a mixture of methane and air, though the temperature of the flame is lower than for conventional liquid fuels [223]. Methane vehicles have better cold-start and warm-up characteristics, and it can be used in the spark ignition combustion engines with minor modification [224].

Table 5. Comparison of methanol, DME and methane properties

	Methanol	DME	Methane	Petrol	Diesel
Formula	CH_3OH	CH_3OCH_3	CH_4	C_7H_{16}	$C_{14}H_{30}$
Energy density $_{LHV}$ (MJ/kg)	19.7	28.62	55.6	43.47	41.66
Carbon content (wt. %)	37.5	52.2	74	85.5	87
Flash point (°C)	12.2	-41	-188	-45	100–130
Ignition temperature (°C)	470	350	537	246–280	210
Cetane number	-	>55	-		40–55
Octane number	100	-	130	90–100	-
Odour	-	+	-	+	+
Toxicity	+	-	-	+	+
Corrosive	+	-	-	-	-
Reactivity	Medium	Medium	Low	Medium/High	Medium/High

6.3 Infrastructure for deployment of electrofuels

Alternative fuel vehicles are becoming more important as the European Union has imposed an obligation to develop an infrastructure for alternative fuels. Only few alternative fuels are completely compatible with existing petrol and diesel engines, while most require some alterations to ensure the compatibility; in some cases, a new vehicle is necessary. Interesting development of the vehicle market happened in Brazil, where vehicles running only on ethanol were introduced in 1979, but they were slowly replaced by flexi-fuel vehicles (FFV) as the price of petrol dropped [225]. Flexi-fuel vehicles are relatively common in Europe, with Sweden being a leader with around 250,000 FFV, which is somewhat 70% of the total amount of those vehicles in Europe. FFV can operate on two or more fuels that are stored in the same tank, and there are available FFV that can run on 100% alcohol fuels. Development of methanol flexi-fuel vehicles was introduced in California in the 1980s by Ford, producing FFV capable of running on M85 [226]. Methane vehicles are deployed more than other alternative vehicles; however, depending on what type of vehicle is used, the infrastructure costs can be very high.

This section gives a brief overview of the historical development and the current status of methanol, DME and methane vehicles, followed by the tank-to-wheel efficiency of these fuels. As the particular interest is in using electrofuels for heavy-duty vehicles, the overview will mainly focus on heavy-duty vehicles, but in some cases, data for light-duty vehicles will be presented.

6.3.1 Status of vehicles running on methanol, DME and methane

Using methanol as a transport fuel is not a novelty [227], and methanol was used for many years in different countries between the 1970s and 1990s. Methanol was deployed as a transport fuel in California (US) for many years [93], during which 100 fuelling stations were built and approximately 20,000 ICE were used for transportation. In Germany, methanol blends were introduced in the 1960s, with 2% blends of methanol and petrol [228], which is almost the same as the restriction for methanol blends in the EU today. New Zealand, Sweden and Germany tried to introduce vehicles with M15 blends in the late 1970s and at the beginning of the 1980s [94]. Methanol has been used for race cars since the 1960s, as it is safer than petrol when it comes to fire regulation and it has a higher octane number, meaning better engine performance [44]. China is a leader in methanol integration in the transport sector. There are five different methanol blends that are available on the Chinese market: M5, M10, M15, M85 and M100 [93]. Out of 11 provinces that are deploying methanol as a transport fuel in China, some provinces are also testing different blends, such as M30, M45 and M60 [217]. There are provincial and government-supported programmes, and there are provinces where it is not possible to buy a non-methanol blend fuel. Kostka and Hobbs [229] report the political economy of methanol in China and the determinants of governmental support programmes. In the last three years, five automobile companies in China have released five categories of vehicles running on methanol: cars, microvans, van trucks, public buses, and heavy-duty trucks. All of these categories include vehicles that can run on M100 [230]. In November 2014, automobile manufacturer Geely signed a contract for 100,000 M100 vehicles on an annual production basis [231]. The Chinese Ministry of Industry and Information Technology (MIIT) after a year of the methanol vehicle project stated that there are no technical problems with the vehicles and that the emissions are lower than the standards in China [232]. According to Cohn [113], the driving range of methanol vehicles is lower than for diesel vehicles, due to the lower energy density of the fuel. In order to meet the same driving range, a larger tank is needed. Experiences in China state that the vehicle range ratio between petrol and methanol is 1:1.6 [233]. There are many studies on vehicle performance for alcohol fuels and alcohol blends [218–220,234,235]. The conversion cost for adapting petrol vehicles to methanol flexi-fuel vehicles is in the range of €90–260 [236]. In their Fuel Choice Initiative, Israel have introduced methanol as a solution for oil dependency until 2025 [237]. It has also been announced in Sweden that the methanol will be used as a marine fuel for ferries [238].

In recent years, there has been a growing interest in DME as transport fuel, and it has been analysed in different studies [95–97]. Volvo has been a leader in DME heavy-duty vehicles since the late 1990s, when its first development programme was introduced. In Denmark, Hansen and Mikkelsen reported feasibility results of the first-generation DME bus from Volvo [239]. The results of the driving range were similar to methanol. Volvo has announced that limited production of DME vehicles will be launched in 2015 for the US market [240]. DME engine efficiency is very much the same as diesel in the current state of DME engine development[12]. This is also demonstrated by Sato *et al.* [241], showing that a DME truck has the same power and performance as a diesel truck. In the BioDME project [54], Volvo performed truck testing of 10 trucks running on DME, which included 800,000 km of testing. Nevertheless, it is not only Volvo that has been working with DME vehicles. According to [242] there are 11 different vehicles available in Japan and one in China.

Methane vehicles are by far the most deployed alternative vehicles on the market. The latest results for Europe show that there are 1.8 million natural gas vehicles, with 4,191 public and private fuelling stations supporting the fleets [243]. Regional trends show that Iran and Pakistan are leading in the number of NGVs on the market [224]. It seems like compressed natural gas vehicles (CNG) have not been as successful, due to their infrastructure costs and their low operating range. The alteration of petrol vehicles to CNG is possible, but the costs are up to €9,500 [244].

Table 6. Tank-to-wheel (TTW) efficiency for personal vehicles

		[245]	[246]
Fuel	**Type of engine**	**MJ/km**	**MJ/km**
Diesel	Compression ignition	1.5	1.63
Petrol	Spark ignition	1.9	2.11
Ethanol (E85)	Spark ignition	1.9	2.03
Methanol	Fuel cell	1.48	-
DME[13]	Compression ignition	1.53	1.72
Hydrogen	Fuel cell	0.94	0.75
Natural Gas	Spark ignition	1.87	2.32
Electricity	Electromotor	0.5	0.52

Comparison of vehicle efficiency is one of the decisive factors, apart from the fuel production efficiency. It is difficult to obtain tank-to-wheel (TTW) efficiency for different fuels that are comparable, as the TTW is dependent on the driving cycle. The summary of the data for both personal vehicles and trucks or buses is outlined in Table 6 and Table 7. The data for personal vehicles is given for the comparison, in order to show that the trend of efficiency between different vehicles does not change for buses and trucks. This dissertation analysed only solutions for freight transport, and data for personal vehicles was not used further on.

[12] Henrik Salsing, Volvo Group (personal communication, June 16, 2014)
[13] The same assumption is applied for methanol.

Table 7. Tank-to-wheel (TTW) efficiency for buses and trucks

	Type of vehicle [ref.]	**Truck** [245]	**Bus** [245]	**Bus** [247]
Fuel	**Type of engine**	**MJ/km**	**MJ/km**	**MJ/km**
Diesel	Compression ignition	10.87	16.86	16.4
DME[14]	Compression ignition	10.87	-	15.6
CNG	Compression ignition	12.28	19.05	21.5
Diesel hybrid	Compression ignition	-	12.97	12.7
Ethanol	Compression ignition	-	-	16.5

6.3.2 Filling infrastructure requirements

More than 1,200 methanol-filling stations in China offer methanol blends [233], and the price for M100 is 34% of the petrol price, making it very affordable. Compared to expensive infrastructure for CNG, existing petrol stations can be converted to methanol or the capacity can be added, with the cost range of €30–61,500 [248]. Hart *et al.* [249] suggested that the cost of conversion of a petrol station to methanol is around £30,000 for a single tank. The fact that the given cost references are 15 years old should be taken into consideration. In their report from 2010, Bromberg *et al.* [93] report the cost of the station to be €44,000, which is still in the same range as older references. The United States Energy Security Council Report [217] from 2013 gives similar costs to previous references: €17,500 for a midgrade conversion of a filling station to M85 and approximately €53,000 for a new pump. It is assumed that the cost for a DME filling station will not vary from the cost for a methanol station. In the bioDME project, four filling stations were adapted for DME, and the investment cost per station was €200,000 [54].

The CNG stations are more represented around the world than methanol or DME stations, and Denmark currently has nine CNG stations. The US Department of Energy [250] reported that the cost of a CNG station ranged from €40,000 up to €1.5 million, depending on the size and the application. Another US source [217] reports that the cost for CNG is from €600,000 to €880,500. In the report on the national status of CNG filling stations in Germany [251], the cost for a station, excluding the building cost, was €190–350,000. Based on this cost overview, it seems that converting the existing filling infrastructure to methanol/DME is less costly than for CNG. The summary of the filling infrastructure costs is outlined in Table 8.

[14] The same assumption is applied for methanol.

Table 8. Filling infrastructure costs for methanol/DME and methane (CNG)

Methanol / DME filling stations	Investment cost of converting petrol station	M€/station	0.03	0.06	0.04	[93,248]
Methane filling stations (CNG fuelling station)	Investment cost for CNG filling station (including building cost)	M€/station	0.3	1.5	1	[250]
	Investment cost for CNG filling station (excluding building cost)	M€/station	0.19	0.3	0.25	[251]

6.3.3 Summary of the system architecture and infrastructure costs for electrofuels

The conversion of transport infrastructure is very time- and cost-intensive; thus, maximising the use of existing infrastructure when introducing new fuels should have priority. This is the main objective of deploying electrofuels in the transport sector, as the infrastructure can be adapted to these fuels. Based on the production side of electrofuels, the requirements and the technology status are different depending on the fuel pathway. Technology development of high-temperature electrolysis is the most uncertain part of the cycle; however, as noted before, the first demonstration plant for fuel production has been inaugurated. The data gathered in the demonstration plant could potentially remove the high level of uncertainty, as the operation hours and degradation rates need to be improved. The development of biomass gasification is on a high level and there are many demonstration and commercial plants already in place. In all pathways, there is high potential for synergy between production elements. Fuel synthesis is a highly exothermic process that favours high-temperature electrolysis, and gasification as the excess heat can be used for this process. If the electrolysis is pressurised, then it can be better integrated with the synthesis. In cases of using steam electrolysis the excess oxygen can be used for oxygen-blown biomass gasification [252]. Exploiting the synergies in the production cycle can enable the efficient production route, as the individual technologies complement each other.

The main resources for electrofuel production are biomass and carbon dioxide. Biomass resource potential for Denmark is high enough to cover the needs for biomass in a 100% renewable energy system, including the transport sector if the biomass is used for bioelectrofuels. The calculations on availability of carbon dioxide resources for the same type of system confirm that even in a 100% renewable energy system in Denmark there will be enough carbon dioxide for CO_2 electrofuel production [89]. The amount of CO_2 emissions available is based on biomass used in the heat and power sectors as well as industry. With regard to the water use for electrolysis, using water for hydrogen production, for producing all of the liquid fuels for the transport sector which cannot be electrified, would consume close to 1% of the total water consumption of Denmark [117,253]. This represents a very small fraction of the total water consumption, and it should not present a threat to drinking water or water used for agricultural purposes. Handling of the fuel seems not to be a major issue as both methanol and methane are commonly used in the existing system. The use of the fuels in existing vehicles requires alteration of the vehicles or, in some cases, the purchase of new vehicles. The filling infrastructure can be adapted to methanol/DME; furthermore, from a cost perspective, the adaptation of the infrastructure to these fuels is less costly than for methane. The summary of the infrastructure requirement is outlined in Table 9.

The most cost-intensive elements of the production cycle are the biomass gasification facility, carbon capture & recycling, and electrolysis. However, the costs of electricity needed for powering electrolysers and the investment in wind power plants are the main expenditure in fuel production (see Chapter 7). These costs cannot be disregarded as the investment in the wind capacity is due to the fuel production. The costs of the SOEC electrolyser and biomass gasification are subjected to uncertainty, as the projection of the future costs is not necessarily a real representative of the future costs. However, it is important to differentiate that the projected cost of the biomass gasification plants is based on the current data of operating facilities, while the SOEC costs are expectations of the technological development; thus, it is difficult to provide highly accurate costs.

Table 9. Summary of the infrastructure requirements and potential issues

	Biomass hydrogenation pathway (bioelectrofuel)	CO_2 recycling pathway (CO_2 electrofuel)
Resources supply	▪ Using existing infrastructure that is used for bioenergy and biofuel plants ▪ Transportation of biomass with trucks or by rail ▪ Limits on available biomass for transport of fuels ▪ Requires local small-scale biomass gasification plants to reduce transport or large-scale gasification if transport is not a major cost ▪ The water resources are evenly distributed	▪ Using technology for capturing CO2 from stationary sources (in future air capturing when commercialised) ▪ CO_2 gas cleaning treatment and new pipeline transportation
Conversion process	▪ New biomass gasification facilities needed ▪ Commercialisation of high-temperature electrolysis needed ▪ Existing chemical synthesis processes can be utilised for fuel synthesis	▪ Commercialisation of high-temperature electrolysis needed ▪ Existing chemical synthesis processes can be utilised for fuel synthesis
Fuel distribution /refuelling facilities	▪ Use existing infrastructure for fuel delivery to refuelling facilities (trucks) ▪ Large distribution networks and storage facilities already in place, but may require minor modifications ▪ Alteration of vehicles to methanol, DME or methane needed, or new vehicles can be purchased ▪ Adding new fuel capacity to existing gas stations or complete conversion of it ▪ In the case of methane, expanding infrastructure for CNG. Use a natural gas network for methane distribution.	
Technology status	▪ High-temperature electrolysis is critical technology (still on an R&D level), but it is possible to use alkaline as established technology ▪ Improvements and further developments of biomass gasification, due to different biomass types and properties ▪ Smaller issues with vehicle alteration in the case of methanol/DME	▪ High-temperature electrolysis is critical technology (still on an R&D level), but it is possible to use alkaline as established technology ▪ Smaller issues with vehicle alteration in the case of methanol/DME ▪ Potential issues with syngas storage and transportation (if necessary to use)
Costs	▪ Primary cost is in the gasification facility, electrolysis, and investment in wind and electricity price for powering electrolysers	▪ Primary cost is in CO_2 capturing, electrolysis, and investment in wind and electricity price for powering electrolysers
Environmental impacts	▪ Biomass resource exploitation limits, land use changes ▪ No significant improvements in the tailpipe emissions compared to fossil fuels	▪ Neutral or beneficial as the CO_2 emissions are recycled

6.4 SYSTEM DESIGN

The design of the system depends on the system elements and the possibility of establishing new infrastructure in the current system. It is possible to have a decentralised and centralised solution, depending on the capacity of the electrolysers, carbon capturing, and gasification. The transportation of carbon dioxide necessary for CO_2 electrofuel pathways is a known technology, but according to the cost assessment, the increase in distance increases the cost of transportation. Therefore, it would be more feasible for the transportation distance to be shorter, or even avoiding the transportation by combining the production elements at one site location. As there was no cost assessment of syngas transportation and the properties of the gas require new pipeline construction, as it is not possible to transport it with a natural gas pipeline, system design excluded this as an option for electrofuel production. This implies that the electrolyser units and fuel synthesis should be at the same location. This is not regarded as a problem, as the benefit of having an electrolyser and synthesis plant at the same location is using surplus heat from chemical synthesis for high-temperature electrolysis, exploiting the synergies of these two technologies. This synergy can be further established in the case of a bioelectrofuel facility for gasification, as the gasification is also a high-temperature process.

At the current stage of technological development, the CO_2-to-electrofuel plant in Iceland is producing 4000 t/year of methanol, which is rather low. If this capacity is used for covering the total transport demand for liquid fuels by CO_2 electrofuels, this would result in 1500 plants in Denmark. This is not a realistic scenario, as the distribution of carbon dioxide emissions is concentrated around urban areas. If the production is increased to 40,000 t/year, the number of plants will accordingly be reduced to 150, which is still rather a high number for a small country like Denmark. It is expected that the production capacity will be higher in the future, which could result in a smaller number of plants. The benefit of having production plants closer to the city is that the waste heat from the production process could be used for district heating. If it were assumed that the plants should be located closer to the bigger cities, which are the largest CO_2 emitters, this could be done by having five centralised plants. The needed capacity of the synthesis plant would still be below the currently developed technology [254]; however, the capacity for electrolysis will be very high (around 1200 MW). The decentralised solution could have 30 plants distributed around the country, which would imply 205 MW of electrolysers. The problem of providing the hydrogen could arise as the development of SOEC electrolysers for hydrogen production or co-electrolysis is based on future predictions. However, if the CO_2 hydrogenation is to be used, then alkaline electrolysis can be used instead of SOEC if the development does not reach its predictions. The largest running alkaline electrolyser system is 160 MW [58] and it is expected that the system capacity can be expanded. Unfortunately, alkaline cannot be used in the co-electrolysis pathway, as it is not possible to carry out this process with the alkaline electrolysis. As both processes require the same net resource use (shown in Chapter 5), the choice could be to simply use the CO_2 hydrogenation for electrofuel production.

A biomass hydrogenation pathway would require fewer production plants, but still the potential problem with scaling the electrolyser capacity could influence the sizing of the plants. There are benefits from a synergy perspective if the biomass gasification is located close to the synthesis plant, which is also beneficial for high-temperature electrolysis used in the process. The biomass transportation costs should be minimised by locating production plants closer to the available resources. Denmark is rich in straw resources [255], so the assumption of building five plants for this pathway and connecting the surplus heat with the district heating in the cities should be possible.

7 FEASIBILITY OF ELECTROFUELS IN FUTURE ENERGY SYSTEMS

The energy system analysis was done in three stages and presented in three publications [117,118,256]. The publications covered the following parts of the analysis: the ability of different electrofuel pathways to integrate fluctuating renewable energy resources, calculation of the fuel production costs with and without system balancing costs, and investigation of the socio-economic perspective of these pathways as part of the 100% renewable energy system (see Figure 16). The feasibility study analysed electrofuels as a possible alternative to biofuels and the results were compared with electrification, hydrogen, first- and second-generation biodiesel, two bioethanol scenarios, and biogas as transport fuel alternatives. This was not done in all stages, but every stage included a comparison with certain biofuels. After the pathway creation and the details on the production cycle parts, it was possible to analyse different pathways in the energy system analysis tool and perform technical energy system analysis and a socio-economic feasibility study.

All performed steps include sensitivity analysis due to the uncertainties about resource costs and different technologies' costs in the future. To begin with, the preliminary feasibility analysis conducted in the first publication was repeated in the new model due to some modelling changes implemented after the publication took place. Secondly, the comparison of using alkaline electrolysers instead of SOEC electrolysers was done in order to see what the consequences could be of using alkaline instead of SOEC, if they do not reach the predicted technological development. Moreover, the sensitivity analysis with different SOEC and offshore wind investment costs, reflecting 2020 and 2030 predicted costs, was conducted in order to see how these two elements affect the socio-economic costs of scenarios. Finally, the fuel production costs were calculated for the 2050 scenario in EnergyPLAN for different technologies and resources included in the creation of a fuel production price. The overall efficiency of the pathways is presented, including vehicle efficiency and sensitivity analysis of different trends in vehicle efficiencies.

This chapter is divided into three parts that are related to the publications listed below.

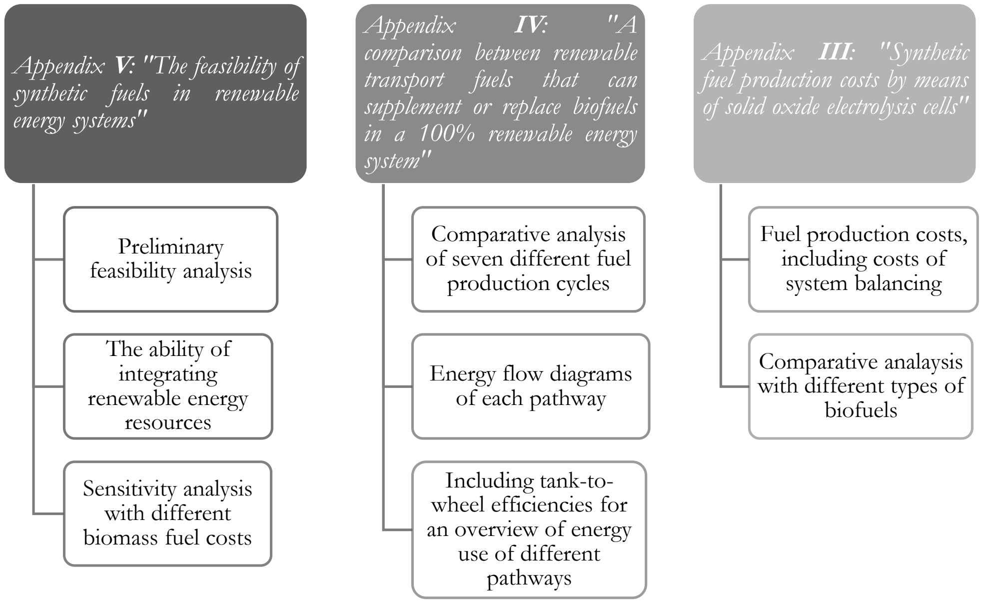

Figure 16. Overview of the different parts of the analysis and the connected publications

7.1 Technical energy system analysis and socio-economic feasibility study

Preliminary analysis was conducted in the paper "The feasibility of synthetic fuels in renewable energy systems" [256]. This analysis was performed in EnergyPLAN version 9. At the time of the analysis, EnergyPLAN did not have integrated calculations for electrofuels; therefore, the analysis was conducted by a different way of modelling. A number of limitations of this modelling, compared to the new model, could have influenced the results obtained from the analysis. The results of the analysis should thus be looked at as indicative to understand the potential of these fuels in the energy system. The preliminary analysis raised the knowledge of the modelling of these pathways in EnergyPLAN, which was consequently applied in the model. The next version – EnergyPLAN version 10—included modelling electrofuels in a more detailed way, with transport fuel supply having been restructured to include electrofuel production. The model was further developed, but the modelling of electrofuels did not change further [257]. The analysis was repeated with version 11.4 of the model and it included the gained knowledge on pathway creation and energy flows, which consequently influenced new results.

7.1.1 The analysis update

The new analysis included three electrofuel pathways with two fuel outputs—methanol/DME and methane—to represent both liquid-based fuel and gaseous fuel.

These pathways were compared with first-generation biodiesel as a well-established technology, second-generation biodiesel, and second-generation bioethanol (see Table 10). All pathways are integrated in the 100% renewable energy system; thus, the same names were allocated when referring to energy system scenarios. The analysis objective was to investigate the ability of fluctuating renewable resources integration, which reflects the system flexibility, the biomass used in the system, and socio-economic costs. The ability of the integration of fluctuating renewable resources is investigated by measuring Critical Excess Electricity Production (CEEP) with different offshore wind capacities installed. The rise in CEEP indicates an existing lack of flexibility in the system. The flexibility of the systems is measured by the integration of wind capacities with a focus on installed offshore wind capacities, while the onshore capacities were fixed in order to be able to do a cross-scenario comparison. Furthermore, the analysis included the overall biomass consumption in the energy system as limiting the use of biomass resources is prioritised. The socio-economic costs are divided into: (1) investments in the energy system, (2) investments in the transport sector, (3) overall operation and maintenance costs, and (4) fuel costs for the system. The socio-economic analysis was done on the basis of technical energy system analysis. This type of analysis enables the simulation of the energy system without restraints imposed by economic infrastructure.

Table 10. Transport fuel pathways considered

Pathway	***Type***	***Short description***
Biofuel	Biodiesel – 1st generation	Transesterification of vegetable oils and fats to liquid fuel for transport
	Biodiesel – 2nd generation	Biomass-to-liquid process (BTL)
	Bioethanol – 2nd generation	Second-generation bioethanol with C5 sugar utilisation
Bioelectrofuel	Biomass hydrogenation	Gasifying biomass and boosting it afterwards with hydrogen from steam electrolysis, followed by chemical synthesis
CO_2 electrofuels	CO_2 hydrogenation (CO_2 hydro)	Recycling of carbon dioxide emissions for fuel production by combining carbon dioxide with hydrogen from steam electrolysis, followed by chemical synthesis
	Co-electrolysis	Recycling of carbon dioxide emissions for fuel production by a co-electrolysis process of steam and carbon dioxide, followed by chemical synthesis

The technical energy system analysis focused on the transport sector in a reference system CEESA 2050 Recommendable scenario [89], which included transport energy demand, production capacities of electrolysers, offshore wind, biomass gasification, chemical synthesis, their efficiencies, and storage capacities. The reference scenario included the fuel mix of bioelectrofuel and CO_2 electrofuels produced by CO_2 hydrogenation. The transport infrastructure costs (including vehicles) are kept the same for all scenarios, while the fuel mix and investments in technologies necessary for fuel production are added. The analysis was done in such a way that the energy system scenarios were balanced in terms of CEEP and the gas balance, so they could be comparable. The EnergyPLAN model simulates the operation of the energy system by reducing the demand for natural gas in the system when biogas and/or syngas is created, so the output in 100% renewable energy scenarios has a biogas/syngas grid instead of a natural gas grid. The gas balance is important as it includes import and export, utilisation of gas storage, and regulation strategies to minimise the exchange of gas to and from the system. All systems analysed are closed self-sufficient systems, as this is the only way in which to analyse the fuel efficiency and the abilities of electrolysers to improve the fuel efficiency of the system. This way of analysis enables seeing the technical potential of the different scenarios to integrate fluctuating renewable resources, seeing the fuel efficiency of the scenarios, and analysing the total socio-economic feasibility of created energy system scenarios. The same regulation strategies were used for all energy system scenarios. In all scenarios, the fuel demand to be met by different types of liquid or gaseous fuels is 32.15 TWh, while the rest of the transport demand was met by electrification. The results are presented while focusing on three criteria: biomass consumption, system flexibility, and socio-economic costs (as elaborated before).

Table 11. Investment costs for plants included in the analysis. 2050 investment costs for the first-generation biodiesel, fuel synthesis, and biomass gasifier are assumed to be the same as for 2030. The interest rate for all investments is 3 per cent.

Type (year)	Unit	Investment (M€/unit)	Lifetime (years)	O&M (% of investment)	Source
Biomass gasifier (2050)	MW_{syngas}	0.316	25	7	[183]
Biodiesel plant – 1st generation	$MW_{bio\ input}$	0.27	20	1	[245]
Biodiesel plant – 2nd generation	$MW_{bio\ input}$	1.89	20	3	[151]
Bioethanol plant – 2nd generation	$MW_{bio\ input}$	0.435	20	7.68	[151]
Fuel synthesis plant (2050)	$MW_{fuel\ output}$	0.55	20	3.48	[245]
SOEC electrolyser (2050)	MW_e	0.28	15	3	[40]
Offshore wind (2050)	MW_e	2.1	30	3.21	[183]

In Table 11, the main economic assumptions for various technologies used in this analysis are outlined, which are divided into the investment costs of production units, lifetime and fixed operation, and maintenance costs. Table 12 lists the data for carbon capture, feedstock expenses, and fuel handling costs. This is the main economic data that is related explicitly to the scenarios that are analysed, and the rest of the investments in the energy system and transport sector are kept the same for all scenarios.

Table 12. Feedstock costs, fuel handling and carbon capture

	Unit	Costs	Source
Carbon capture	€/t	30	[147]
Straw or wood, incl. pellets	€/GJ	6.2	[258]
Green energy crops	€/GJ	4.7	[258]
Fuel handling	€/GJ	4	[258]

The biomass consumption for the whole energy system is illustrated in Figure 17. As the CO_2 electrofuel scenarios are designed not to include any direct biomass use in the scenarios, but rather to recycle the emissions created by biomass used in other energy sectors, the biomass consumption of those scenarios is the lowest. There are no differences between scenarios even with a different fuel output, as there is no direct connection of biomass used for the fuel production. The 2G bioethanol and biodiesel scenarios are the highest biomass consumers, and if compared to the scenarios that do not use biomass for fuel production, the consumption of biomass in the transport sector for biodiesel is higher than the overall biomass consumption in the whole energy sector of CO_2 electrofuels. The biomass consumption of bioelectrofuel scenarios varies based on the fuel output. This is due to the different biomass-to-hydrogen ratio for methanol/DME and methane production. Consequently, the methane scenario uses less biomass in the transport sector than does the methanol/DME scenario. However, this scenario uses more biomass for combined heat and power production.

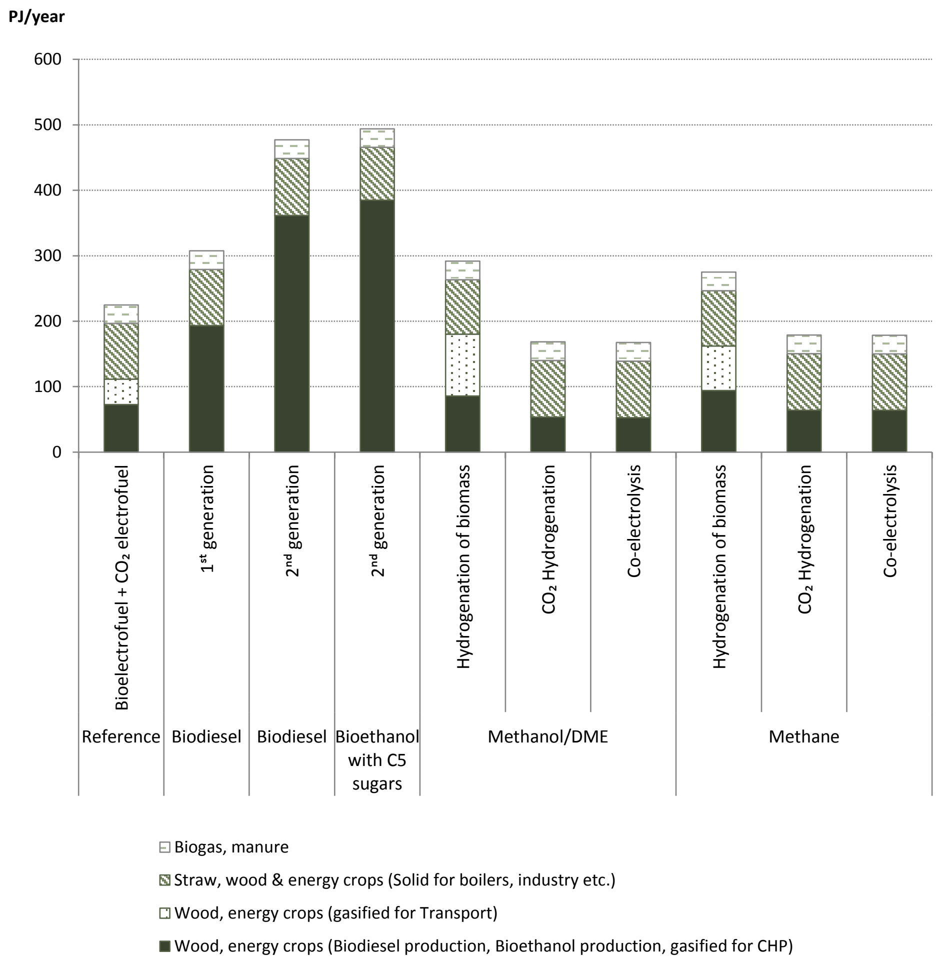

Figure 17. Biomass use in overall energy system for meeting the same transport fuel demand

Systems are compared based on the electrolyser and offshore wind capacity installed, as the onshore wind capacity was fixed in the reference scenario to 4454 MW. The energy system is capable of integrating 20–25% of wind capacities without significant changes [89]; however, higher capacities than that need to be followed by technologies that can facilitate wind power integration. The capability of installing more wind in the system in electrofuel pathways is connected to the electrolyser capacities installed (see Figure 18). This means that the electrofuel scenarios, especially the CO_2 electrofuels, are more flexible than other scenarios as they are capable of integrating very high capacities of wind energy. It can be seen that biofuel scenarios do not allow any wind integration as they do not include electricity in the production cycle, which is an elementary part of electrofuel pathways. The high capacities of the electrolyser and offshore wind in the electrofuel pathways are connected to the electricity demand needed for the hydrogen production necessary for the fuel production. This is also supported by energy storage capacities that are part of the system with electrolysers. The differences in installed wind and electrolyser capacities for methanol/DME or methane scenarios are due to the biomass-to-hydrogen ratio, which reflects back to the electricity demand needed for hydrogen production.

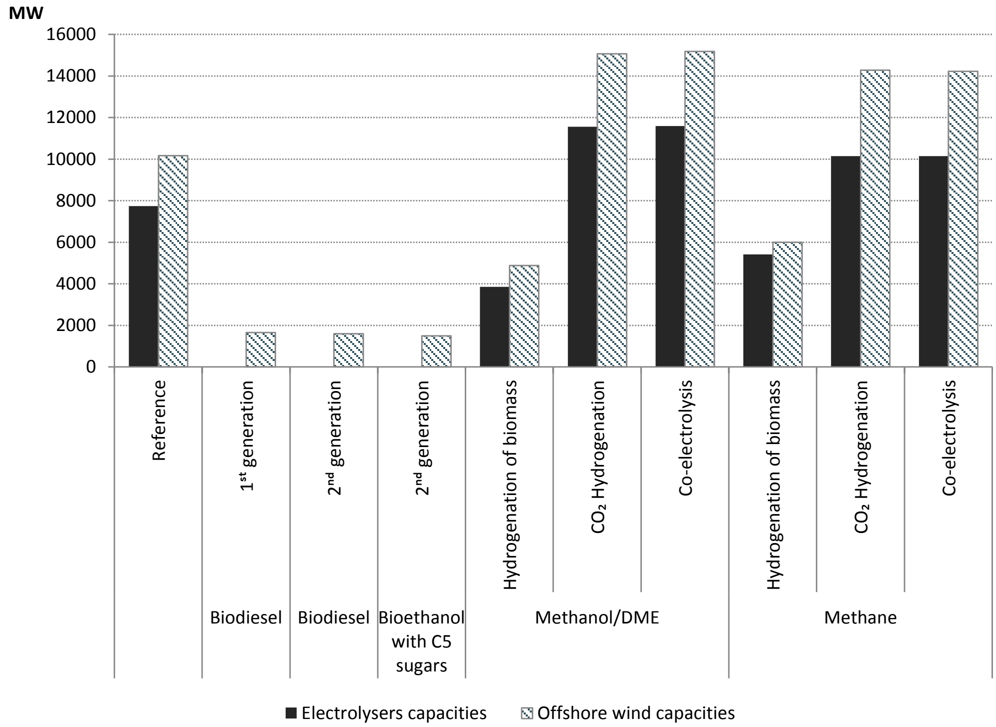

Figure 18. Installed electrolyser and offshore wind capacities for different pathways (same transport fuel demand)

The flexibility of the system is further analysed by measuring the CEEP in the system with different offshore wind capacities installed (see Figure 19). This analysis for electrofuel pathways was conducted only for methanol/DME as a fuel output in order to illustrate the system flexibility. When it comes to interpreting the system flexibility, the lower CEEP, meaning less ascending curves, presents the better ability of the system to integrate renewable energy sources. The CO_2 electrofuels are the most flexible scenarios when it comes to integration of the wind. This was also indicated in the previous graph, where the highest wind capacities are installed in these scenarios. There are no significant differences between the two CO_2 electrofuel pathways in terms of system flexibility, as the variation in the wind and electrolyser capacities installed is negligible. The least flexible scenario concerns biofuel pathways, which give very similar results. This diagram indirectly shows the fuel efficiency of electrofuel pathways as the electrolyser capacities are enabling more wind in the system and reducing the biomass in the system.

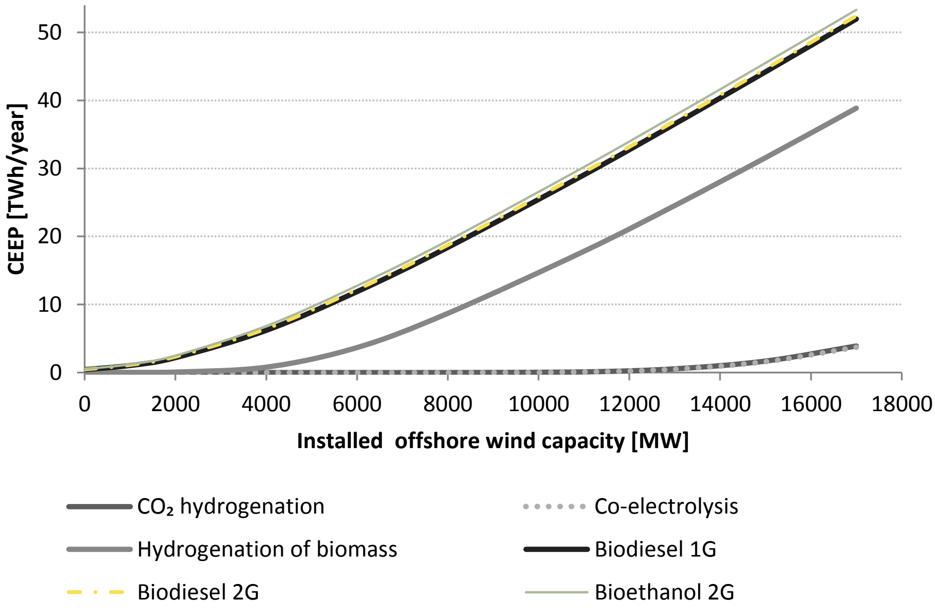

Figure 19. The relation between excess electricity production and installed offshore wind capacities for four scenarios

The socio-economic costs are presented for both the overall energy system and the cost overview of investments in technologies needed specifically for the fuel production. The total annual costs included investments in the energy system and transport sector, operation and maintenance for both the energy system and transport sector, and fuel costs (Figure 20). The overview of the total annual costs for different scenarios indicates that the 1G biodiesel scenario is the scenario with the lowest costs, which is expected as the investment in this scenario is based on well-established technology of biodiesel production. Furthermore, this scenario does not include any investments in wind or electrolyser capacities; therefore, the costs are lower. The most expensive scenarios are second-generation biodiesel and bioethanol, due to the high fuel costs. The CO_2 electrofuel scenarios are following due to the high offshore wind and electrolyser capacities installed. Costs for both of these technologies, especially electrolysers, are based on the future cost predictions.

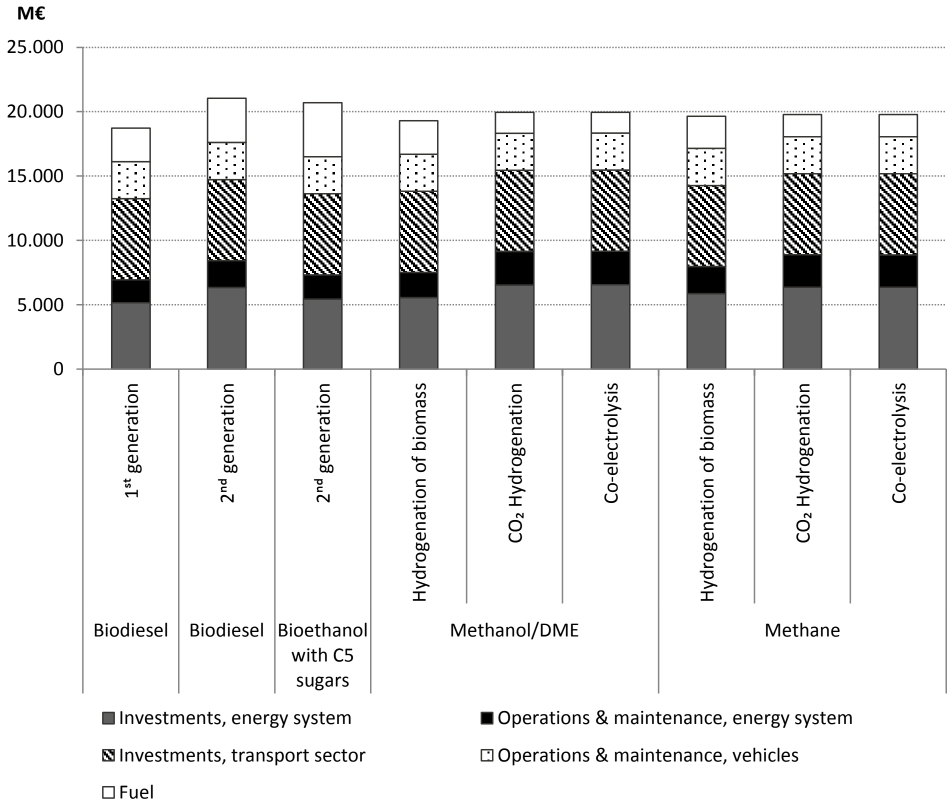

Figure 20. Socio-economic costs of different fuel scenarios in 100% renewable energy system

A better overview of the costs related only to the investments connected to fuel production is given in Figure 21. Here, only investments directly related to fuel production and resources used in the scenarios were compared to the scenario without any liquid/gaseous fuel in the transport sector. Moreover, the sensitivity analysis of different biomass fuel prices (Table 13) was added to see how it influences the costs of different pathways. This sensitivity analysis was done due to the uncertainty of fuel prices in long-term planning. The CO_2 electrofuel scenarios are the most expensive ones from an investment and O&M costs point of view, due to the high investments in wind and electrolyser capacities, which was indicated previously, but this can be clearly seen from the following figure. However, due to the high costs of biomass used for biofuel scenarios, second-generation biodiesel and bioethanol have the highest costs overall. The biggest share of the costs for biofuels and bioelectrofuel concerns the biomass resource costs. For this reason, these scenarios are the most sensitive to the fuel price changes. However, due to the investments in electrolyser and wind capacities for hydrogen production, the bioelectrofuel scenario is more expensive than the first-generation biodiesel.

Table 13. Biomass fuel prices used in the analysis [258]

€/GJ	Low price level	Medium price level	High price level
Straw or wood, incl. pellets	5.6	6.2	8.1
Green energy crops	4.7	4.7	6.3

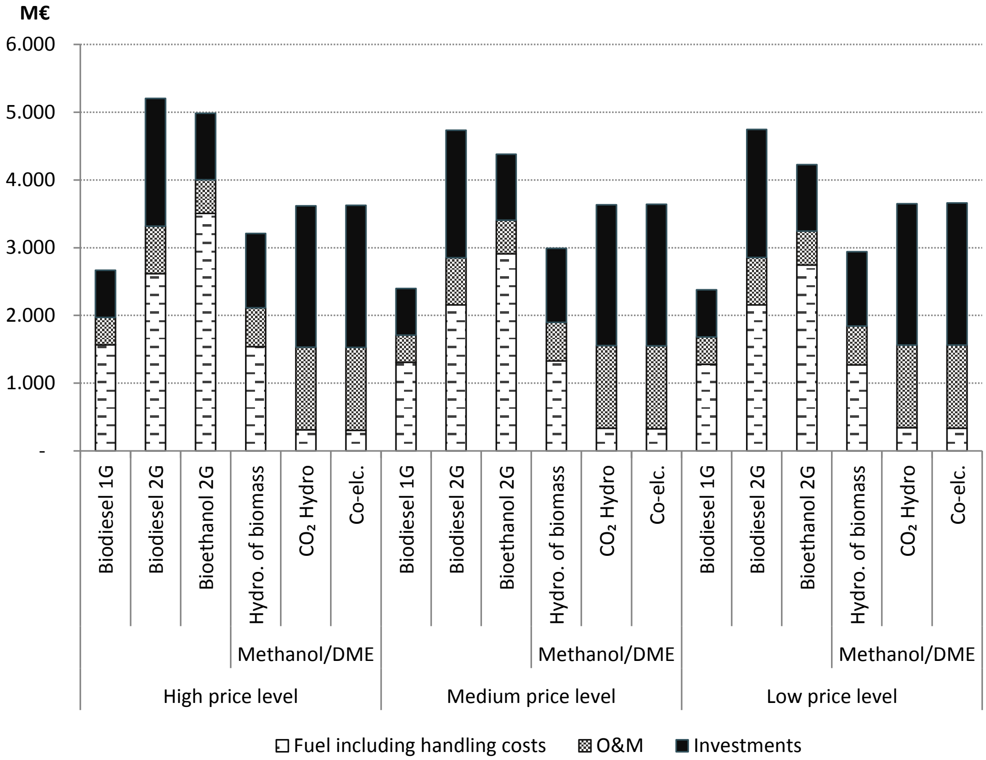

Figure 21. The cost overview of investments only due to the fuel production for methanol/DME and biofuel scenarios

The sensitivity analysis with different economic data for wind and electrolysers (Table 14) was conducted to see which component influences the most system cost variation. The results are presented in comparison with the reference year (2050) to see how much the changes in the investments in these two technologies differ from the costs of the reference year. All scenarios have different offshore wind and electrolyser capacities installed, as outlined before. The sensitivity was calculated so that one variable was fixed and the other was changed. For further clarification, this means that the data for wind investments was changed, while the data for the electrolyser was kept the same and opposite.

Table 14. Economic data input for the wind and electrolyser sensitivity analysis

	Investment ($M€/MW_e$)	Lifetime (Years)	Fixed O&M (% of Investment)	Year
Wind Offshore	17.88	20	3.0	2020
	17.14	25	3.1	2030
	15.65	30	3.21	2050 (reference)
Electrolysers (SOEC)	0.93	5	3	2020
	0.35	10	3	2030
	0.28	15	3	2050 (reference)

Both CO_2 electrofuel scenarios have significantly higher investments in wind and electrolysers; therefore, the results are more sensitive for those scenarios. As expected, the sensitivity analysis shows that the costs are more sensitive to changes in economic data of SOEC, especially for 2020 (see Figure 22).

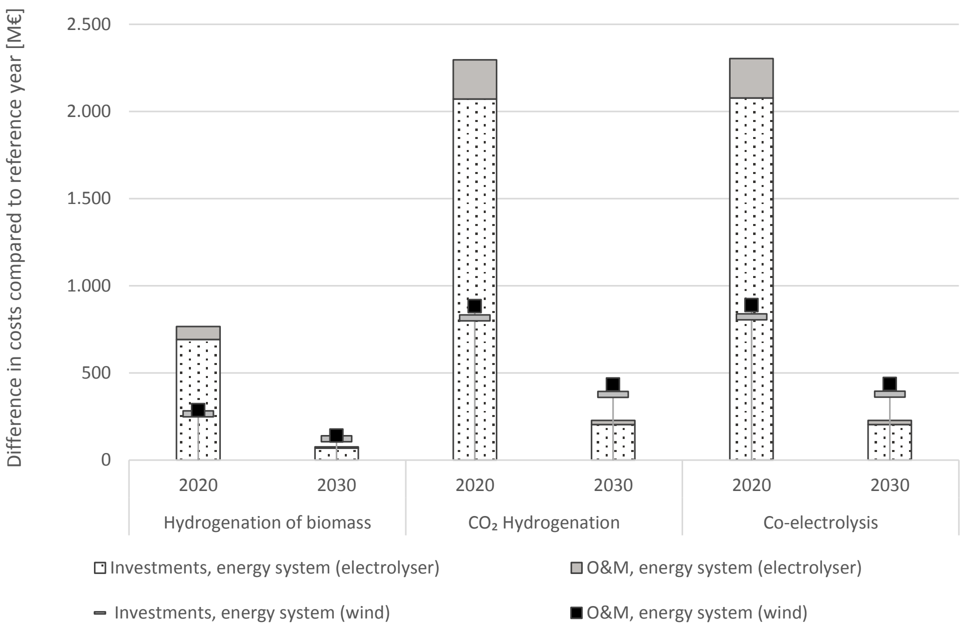

Figure 22. Sensitivity analysis of investments in wind power and electrolysers in relation to the system costs

This is directly connected to the economic data for 2020, as investments are three times larger than in the case of 2050, while the lifetime is reduced by the same ratio. The results for 2030 are more sensitive to the wind investments, as the price difference between the reference year and 2030 for wind is larger than in the case of electrolysers. The correlation between economic data and total system costs is interesting as it shows that the results are sensitive to both technologies and the sensitivity will vary based on what is going to be the final ratio of investments in wind and electrolysers.

7.1.2 Short conclusion

The analysis was used to identify the capability of different fuel pathways to integrate fluctuating renewable resources, focusing on biomass use in the system and the socio-economic costs of the analysed scenarios. The implementation of electrofuels in the energy system showed the improvements in system flexibility, which is an essential feature of 100% renewable energy systems. It was also shown that these pathways are flexible from the end fuel point of view, as the produced synthetic gas can be further converted in different fuel outputs, which was illustrated by showing the results for methanol/DME and methane. The CO_2 electrofuels show high improvements in the integration of wind resources, but that is reflected on the system costs. As these scenarios allow high offshore wind and electrolyser capacity, the investment costs are high, but they are followed by lower fuel costs. The bioelectrofuel scenario showed better flexibility than the biodiesel scenario, but it was not as flexible as other electrofuel scenarios, as the needed hydrogen for the fuel production does not require high electrolyser or wind capacities. This analysis highlighted the impact of electrofuels on the energy system, and showed that due to the limited biomass resources, the investments in these pathways could be worthwhile. From the total system cost point of view, the difference between scenarios is rather low. However, comparing it strictly from the investments for the fuel production and associated resources used in these scenarios, the difference is more apparent. Due to the high biomass demand in biofuel scenarios, their costs are predominantly influenced by the biomass costs associated with production, while in the electrofuel scenarios, investments have the biggest share. As the investments in the electrofuels are mostly connected with investments in offshore wind and electrolysers, the sensitivity analysis showed that these two elements can influence the total investments in the system. This influence can be up to a value of 15% of the reference year system costs in the case of CO_2 electrofuel scenarios. Taken together, these findings suggest that electrofuels could play an important role in the future energy system with restricted biomass resources.

7.2 SENSITIVITY ANALYSIS OF DIFFERENT ELECTROLYSIS TECHNOLOGY

Electrolysers are a crucial element for electrofuel production as they enable the conversion of fluctuating electricity into different fuel outputs whilst providing flexibility for the system. The development, efficiencies and the costs of solid oxide electrolysers are based on the predictions that assume that these electrolysers are going to be commercially available in 2020 and that their costs will be reduced until 2050. Alkaline electrolysers are, on the other hand, a commercially established technology, being in use for many years. As solid oxide electrolysers are still at the research and development level, it was necessary to investigate what the consequences are of using alkaline electrolysis instead of SOEC. The main differences between these technologies are their regulation abilities, efficiency and costs. The most used alkaline electrolysers with bipolar electrodes [259] are designed for stationary grid-connected operation [179] and have a low part-load range [32]. However, there are available alkaline electrolysers with an exceptional dynamic range and operating flexibility, with a very fast response time in the range of 1–3 seconds [179]. It is projected that SOEC can have a fast response if their cell temperature is kept at a high operating temperature (from 0% to 100% power in less than a few seconds) [40]. When it comes to the type of electrolysis that can be done with these two kinds of electrolysers, SOEC has an advantage of conducting oxide ions, meaning that it is possible to perform CO_2 electrolysis and combined steam and CO_2 electrolysis (co-electrolysis). This means that it is not possible to produce the CO_2 electrofuels by a co-electrolysis pathway if alkaline electrolysers are used. However, when it comes to the total energy use of CO_2 electrofuels, both pathways give almost exact results; therefore, this should not be taken as a barrier for alkaline electrolysers for electrofuel production. Regarding the efficiency, alkaline electrolysers have lower efficiencies than SOEC, mainly due to the lower operating temperature. Solid oxide electrolysers have lower predicted investment costs, as they use low-cost materials, while commercialised alkaline electrolysers can use both noble metals, e.g. platinum, rhodium and iridium, and non-noble catalysts [39].

If alkaline electrolysers are used instead of SOEC in the reference system, based on the data outlined in Table 15, the difference between investments on the system level related to the electrolyser technologies used for fuel production can be seen in Figure 23.

Table 15. Investment costs and the efficiencies of alkaline and SOEC electrolysers in the analysis

	Investment (M€/MW$_e$)	**Lifetime (Years)**	**Fixed O&M (% of Investment)**	**Efficiency**
Alkaline	0.87	27.5	4	63.7%
SOEC	0.28	15	3	73%

From the figure, we can see that the investment cost difference of only 3% occurs when alkaline electrolysers are used. Figure 24 shows the difference in costs related to the fuel production; in this case the difference between using alkaline instead of SOEC increases the costs by approximately 9%. This is interesting for several reasons. Firstly, it proves that the socio-economic costs of using alkaline are not substantially higher at the total system costs level, which is important when considering deploying this technology. Secondly, even the lower efficiencies of alkaline did not have a major impact on the fuel efficiency of the system, but the main difference is in the wind capacities installed in order to compensate for the lower efficiencies of these electrolysers.

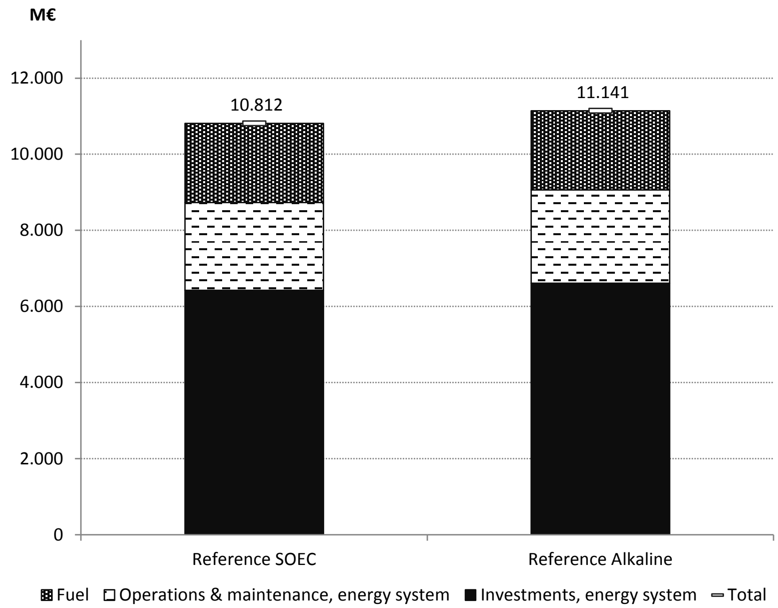

Figure 23. Difference between investments in total system costs based on the input data for alkaline and SOEC electrolysers

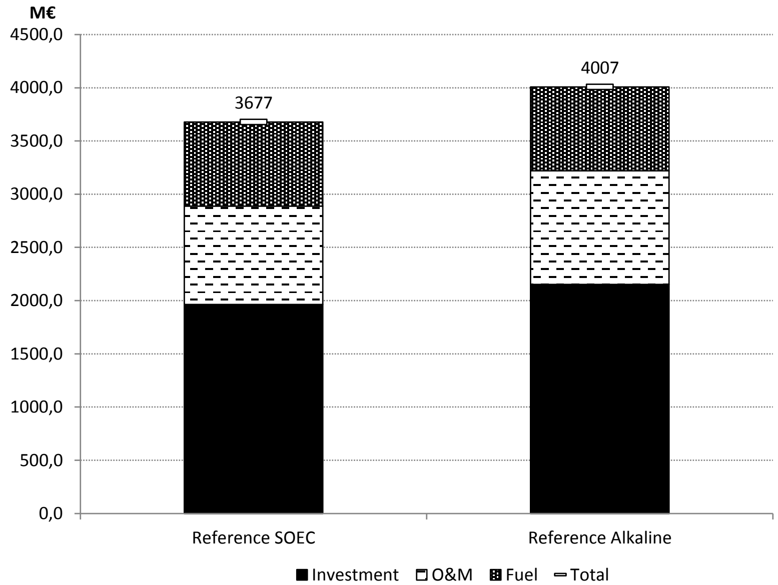

Figure 24. Difference between investments only due to the fuel production based on the input data for alkaline and SOEC electrolysers

The sensitivity analysis of main differences between alkaline and SOEC – investment costs and efficiencies—is based on the data listed in Table 16. Both investments in alkaline and SOEC were altered, but in the case of efficiencies, only alkaline efficiencies were altered, while SOEC was kept at the same value. To the best of my knowledge, there is no efficiency range for steam electrolysis with SOEC; therefore, they were kept at a thermoneutral efficiency.

Table 16. Sensitivity analysis of alkaline and SOEC electrolysers with different economic data and efficiency

	Case	***Investment ($M€/MW_e$)***	***Lifetime (Years)***	***Fixed O&M (% Investment)***	***Efficiency***
Alkaline	**Low Inv. / High effic.**	0.87	27.5	4	67%
	Medium Inv. / Medium effic.	0.97	27.5	4	64%
	High Inv. / Low effic.	1.07	25	4	55%
SOEC	**Low Inv.**	0.28	15	3	73%
	Medium Inv.	0.35	10	3	73%
	High Inv.	0.93	5	3	73%

The results show that all three cases with alkaline electrolysers have higher overall energy system costs (see Figure 25). However, if the SOECs are to be compared to alkaline based on the high-cost case, then the alkaline scenarios with medium and low costs result in lower total system costs. This scenario could occur in reality if the commercialisation of SOECs were to be suspended after 2020 and the costs did not succeed in falling to the predicted level for 2050 of 0.28 $M€/MW_e$.

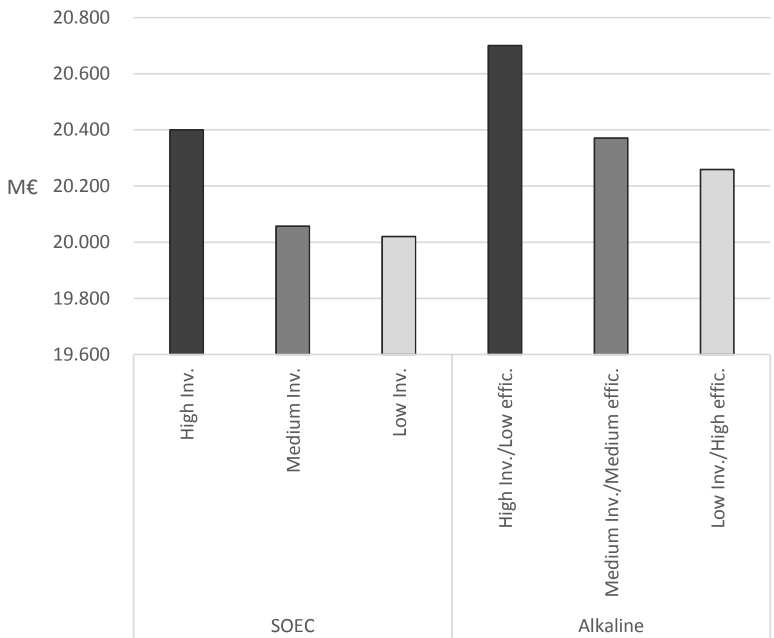

Figure 25. Overall energy system cost sensitivity analysis based on the different economic and efficiency data for SOEC and alkaline

As the reference model has approximately half of the fuels produced by biomass hydrogenation, with the rest being covered by the CO_2 hydrogenation pathway, the sensitivity analysis was done for different biomass prices. The same fuel prices were applied, as indicated in Table 13, while the investments and efficiencies used for electrolysers were taken from Table 15. The biomass fuel price will be directly connected to the biomass demand for bioelectrofuel production, while the fuel price changes will not have an influence on the CO_2 electrofuel part. The results shown in Figure 26 illustrate the same trend as previous results. The alkaline scenarios have higher costs as they use more wind to compensate for the efficiency loss.

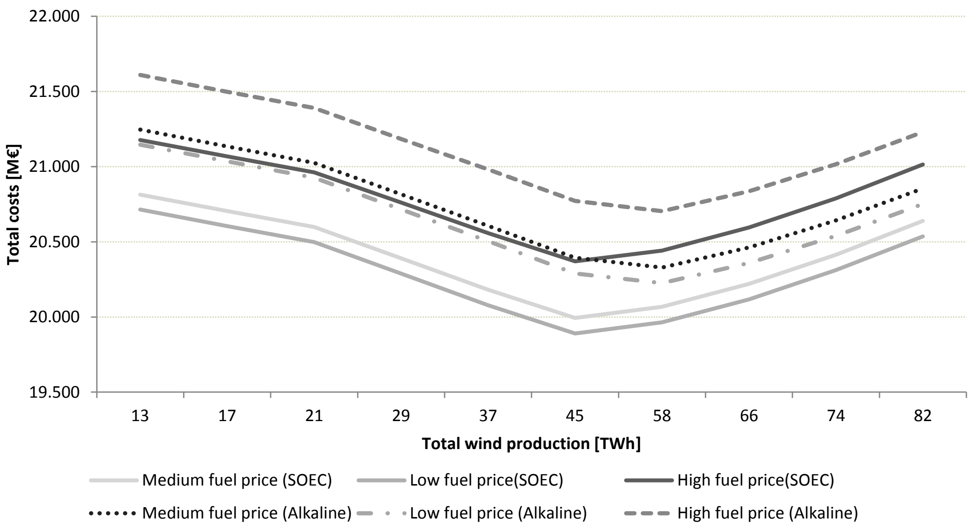

Figure 26. Sensitivity analysis of total system costs with different biomass price levels and different wind penetration

7.2.1 Short conclusion

According to the results of the sensitivity analysis there are no major cost or fuel efficiency differences when deploying alkaline electrolysis instead of solid oxide electrolysers, in case the latter do not reach the predicted development levels. The total system cost difference is rather low; thus, from a socio-economic point of view, alkaline electrolysers should not be disregarded. Only in cases where co-electrolysis is the preferred option for CO_2 electrofuels, due to the synergies between the electrolysis and other parts of the production cycle, will alkaline not be an option, as this process is not possible with this technology. As for the materials used for both technologies, SOECs should be prioritised in case alkaline electrolysis continues to rely on noble catalysts, as platinum, rhodium and iridium are some of the rarer elements of Earth's crust.

7.3 ENERGY AND COST COMPARISON BETWEEN PATHWAYS

Based on the energy flows introduced in Chapter 5, it is possible to compare pathways in terms of the energy they require for meeting the specified transport demand. Furthermore, if the investment costs associated with the technologies used for the specific pathway are included, it is possible to calculate the fuel production costs for producing 1 GJ of fuel for each pathway. Comparative analysis of three electrofuel pathways with different alternatives is presented and the results are based on analyses carried out in Appendix III and Appendix IV. The most similar attempt to compare different fuel pathways in terms of energy and costs was performed by Ajanovic [260]. This research adds to her study that compared electricity-, biomass- and hydrogen-based fuels, and includes new electrofuel pathways. The fuel production prices presented are calculated by using EnergyPLAN and they include the system balancing costs and fuel handling costs. In addition, sensitivity analysis was included in order to investigate the influence of vehicle efficiency variations on the energy required to satisfy the same transport.

7.3.1 Energy comparison between pathways

Seven different production pathways have been considered in this comparative study: direct electrification, hydrogen production, biogas hydrogenation, fermentation, bioelectrofuel and CO_2 electrofuels (CO_2 hydrogenation, and co-electrolysis). As all of the pathways have biomass and/or electricity demand, as main sources of energy, they were compared based on their electricity and bioenergy demand required to meet 100 Gtkm of freight transport. The results presented in Figure 27 are only for freight transport, as it is assumed that electrofuels will be used for this mode of transportation. More details on direct electrification, hydrogen, fermentation, and biogas hydrogenation pathways and results for passenger transport demand can be found in Appendix IV. By assessing the production cycle, it was possible to compare pathways in terms of energy used and resources, which is important when considering fuel pathways in a 100% renewable energy system. In order to calculate needed energy and resources for meeting the same transport demand, it was necessary to calculate the specific energy consumption (MJ/tkm). The vehicle efficiencies based on tank-to-wheel efficiencies (MJ/km) and load factors, which are further converted into specific energy consumption for freight transport (MJ/tkm), are listed in Table 17.

Table 17. Specific energy consumption used for calculating the energy demand for each pathway. The data is based on transport data for Denmark and adapted from [89,245,261].

Fuel	Freight transport		
	Tank-to-wheel efficiency (MJ/km)	Load factor (t/vehicle)	Specific energy consumption (MJ/tkm)
Electric rail	28	85	0.3
Hydrogen	10.5	12	0.88
Methanol/DME	10.8	12	0.91
Methane	12.3	12	1.02
Ethanol	13.7	12	1.15

The results show that the direct electrification is the most efficient form of transportation when it comes to the resources used. The needed electricity for direct electrification is provided by wind energy. It also requires the lowest electricity consumption; moreover, as long as it is produced from the renewable energy sources, this pathway can be considered the most sustainable one. Using hydrogen as transport fuel is very efficient from a resources point of view, especially if we are considering biomass as a restrained resource. The hydrogen is here produced by SOEC that are powered by electricity from wind. However, there are concerns about using hydrogen as a transport fuel, especially when talking about storage systems that could carry enough hydrogen on board, and the infrastructure costs needed for deploying this fuel are significantly higher than for other fuel types [97].

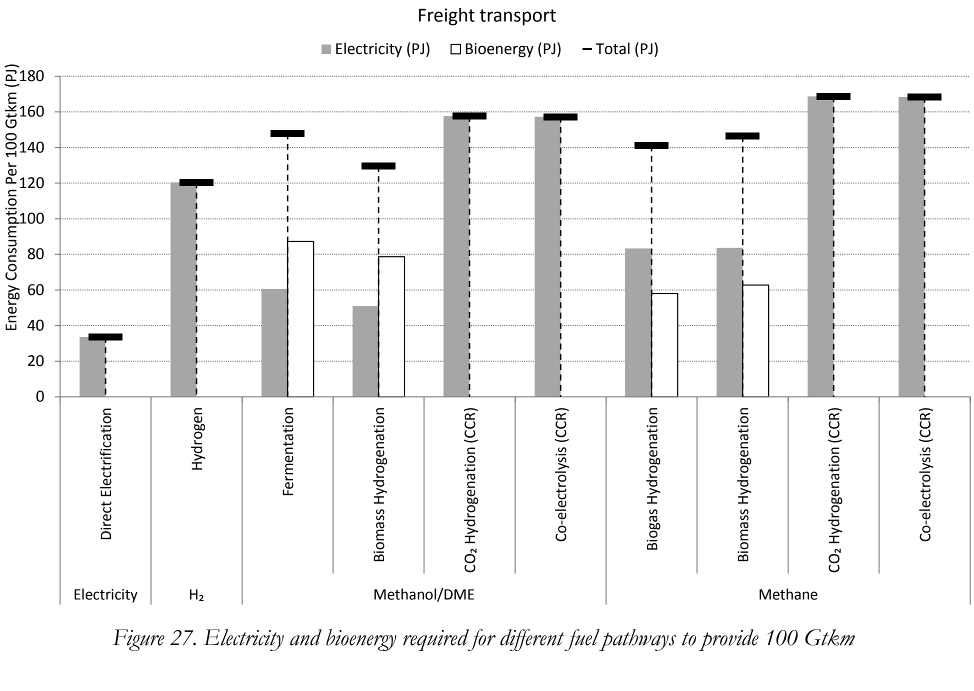

Figure 27. Electricity and bioenergy required for different fuel pathways to provide 100 Gtkm

The fuel outputs of other analysed pathways are divided into methanol/DME or methane. Only electrofuel pathways biomass hydrogenation, CO_2 hydrogenation and co-electrolysis were calculated for both fuel outputs. The fermentation pathway analysed here is very complex. It includes different conversions, sub-pathways for by-product production, and it has the highest biomass use of all pathways. As the main fuel output from this pathway is ethanol and the methanol/DME is produced as one of the by-products, this pathway is not as preferable as just using bioelectrofuel production. A bioelectrofuel pathway is also more efficient from a biomass resource point of view and the total energy needed; it is also not restricted to a specific fuel output, meaning that it can be adjusted to the demand side needs. The biogas hydrogenation gives similar results to the bioelectrofuel production of methane.

The single observation to emerge from the pathway comparison is that the methanol/DME pathways are more efficient than methane pathways. This is correlated with the vehicle efficiency applied and the hydrogen-to-final fuel ratio. If we add the infrastructure perspective to this, the conversion of existing infrastructure to methane is more costly than in the case of methanol/DME, which was elaborated in the previous chapter. Together with the present knowledge included in this analysis, it seems more probable that liquid fuel outputs will be used instead of methane, though this does not mean that there are no potential applications where methane will be used for transport. The remaining electrofuel pathways do not use any bioenergy input, but have high electricity demand needed for fuel production. These pathways confirm that it is possible to produce a liquid or gaseous alternative to transport fuels without any bioenergy input. Based on the analysis carried out, there are no decisive differences between CO_2 electrofuel pathways, and the decision on which pathway should be used in the future will solely rely on the technological development and further demonstration projects.

As it was indicated that methanol/DME as a fuel output at present seems more efficient, it was analysed what would happen with the efficiency of pathways if the methane vehicle efficiency was increased to the level of methanol/DME vehicles. This analysis represents the setting in which gaseous vehicles are as efficient as liquid fuel vehicles. The results of the analysis can be seen in Figure 28. It can be noted that in case the methane vehicles become more efficient, the pathways that have methane as a fuel output subsequently become more efficient from the total energy required than methanol/DME pathways. The total demand for methane dropped by 3% for all pathways.

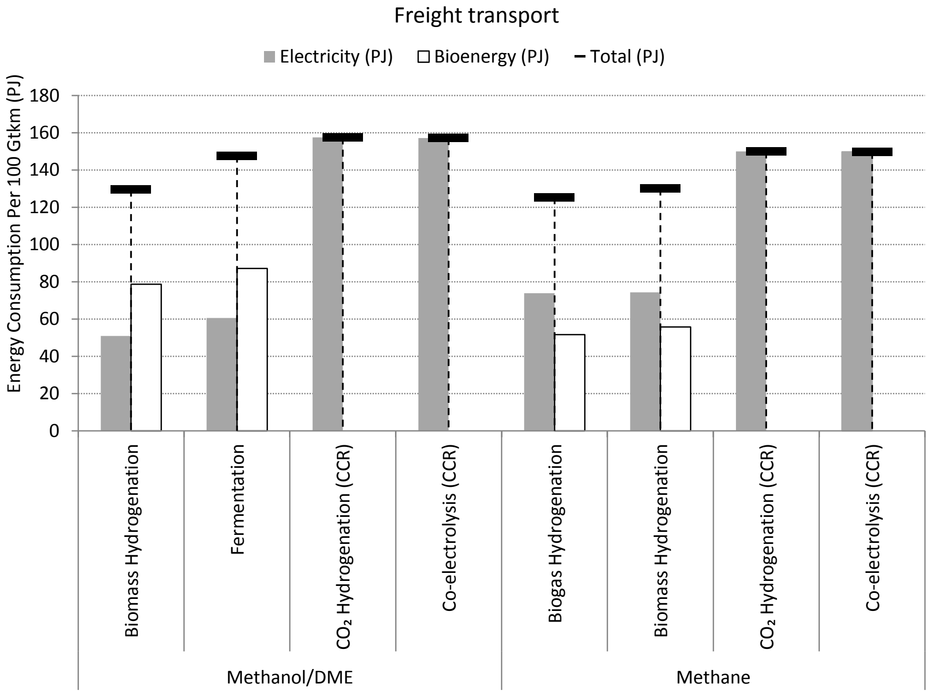

Figure 28. Electricity and bioenergy required for providing 100 Gtkm of freight transport if the methane vehicles are as efficient as methanol/DME vehicles

This confirms the uncertainty that it is still very unclear which final fuel will be chosen in practice in future transport systems. This is mainly connected to the infrastructure cost estimates and potential vehicle development. However, there are indications that significant improvements can happen if methanol is used [218]. In any case, since all electrofuel pathways finish with chemical synthesis, the fuel output can be adjusted to fit the future needs.

Finally, in order to assess what consequences the total energy demand of each pathway would have—a drop or increase in specific energy consumption (MJ/tkm) of 5% and 10%, the sensitivity analysis was carried out. The results presented in Figure 29 show that there is a proportional relation between the changes in specific energy consumption (MJ/tkm) and the total energy consumption (PJ). This confirms that without the assured vehicle efficiency data it is not possible to recommend gaseous or liquid fuel output.

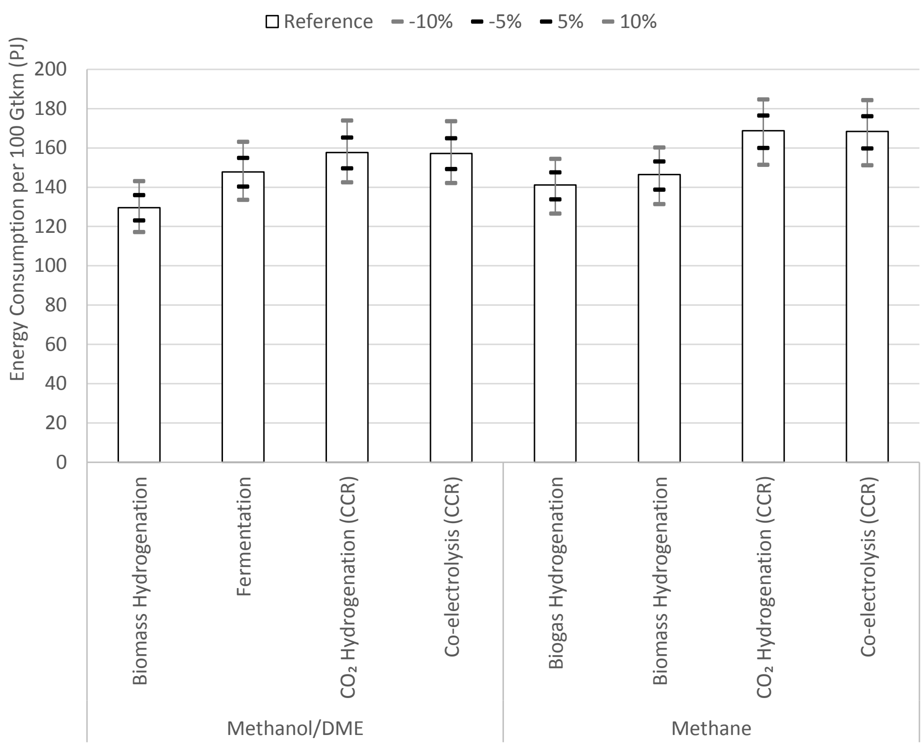

Figure 29. The sensitivity analysis with specific energy consumption for different vehicles

7.3.2 Cost comparison of different pathways

The production cost estimates included two types of fuel output – methanol/DME and methane – for three electrofuel pathways, along with comparable costs for first- and second-generation biodiesel, two types of second-generation bioethanol, and biogas. The production cost calculations are based on the annualised costs of technologies associated with pathways, which are based on the investment, lifetime, and annual O&M costs. The cost data used is presented in Table 11, Table 12 and Table 18. The production costs are calculated by using an energy system analysis tool; therefore, they also include the system balancing costs, fuel handling costs and, in some cases, CO_2 emission costs. The fuel production costs were calculated for the same fuel demand of 32.15 TWh. This cost calculation does not include infrastructure costs or vehicle costs, as the price calculation is based only on the production cycle and excludes the costs of deploying these fuels in the transport sector. The details on the system elements for biofuel pathways are elaborated in [118] and will not be further presented here.

Table 18. Investment costs for additional pathways included in the cost comparison. The interest rate for all investments is 3 per cent.

Type	Unit	Investment (M€/unit)	Lifetime (years)	O&M (% of investment)	Source
Biodiesel – 2nd generation	$MW_{bio\ input}$	1.89	20	3	[151]
Bioethanol plant	$MW_{bio\ input}$	1.82	20	3.69	[245]
Bioethanol plant – C5 sugar	$MW_{bio\ input}$	0.435	20	7.68	[151]
Biogas plant	TWh/year	392	20	6.96	[183]

The results are displayed in Figure 30 for biofuels and biogas, and in Figure 31 for electrofuels with two fuel outputs. The predicted petrol/diesel price for 2050 was added to both figures as a base of comparison. The costs include the breakdown of specific technologies, which forms the price, feedstock, and fuel handling costs, together with CO_2 emission costs where applicable.

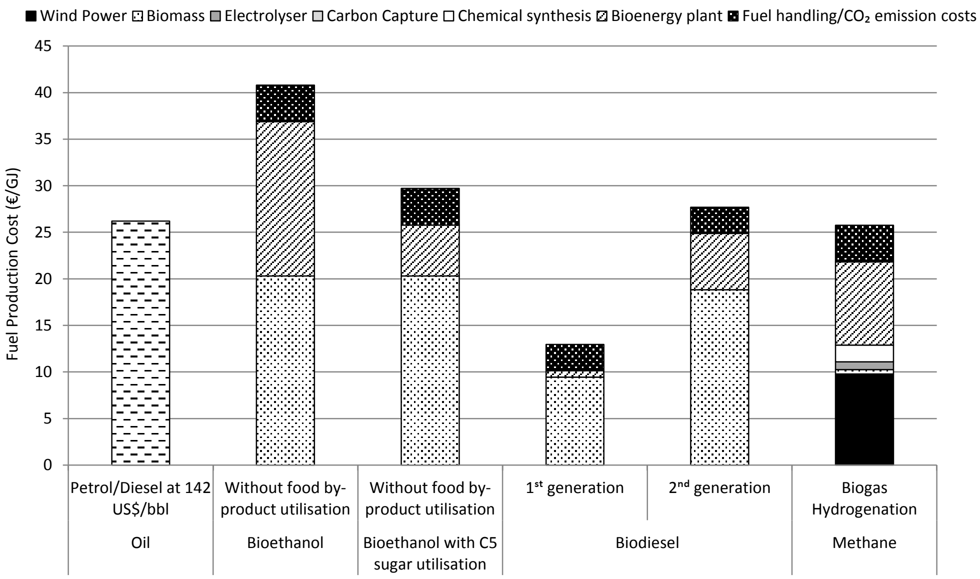

Figure 30. Fuel production costs for biofuels, biogas and petrol/diesel in 2050

The production costs vary due to the complexity of different pathways, their ability to integrate wind production, technology costs used for fuel production, and the biomass used. The overall production prices for alternatives can be taken as relatively low if the risk associated with use of oil is accounted. It can be seen that the first-generation biodiesel has the lowest production costs, while the highest costs are for electrofuel pathways and bioethanol pathways. The first-generation biodiesel pathway uses 33.5 TWh of biomass to produce enough biodiesel to cover the demand, which forms 73%

of its price. The amount of biomass used for production of second-generation biodiesel is even higher, due to the lower efficiency of the process. The bioethanol pathways have the highest production costs, which are followed by the highest biomass consumption. The difference in price between two types of bioethanol production is simply due to the price of the bioethanol production plant. The biogas production price is highly connected to the investments in biogas plants and wind power, which produces hydrogen for upgrading biogas to methane so that it can be used for transport purposes.

When it comes to the comparison of costs between methanol/DME and methane, methanol is the cheaper option in the case of bioelectrofuel production, but in the case of CO_2 electrofuels, methane has lower costs. This comes back to the hydrogen-to-fuel output ratio, as methanol pathways use more hydrogen than methane pathways. Therefore, the wind investments are higher, which reflects on the fuel production price. The scale of difference between methane and methanol/DME is relatively small (approximately 6%), which is not a significant cost difference to speak in favour of one fuel or another. Overall, this difference is to be balanced by the costs of deploying sufficient infrastructure if both of these fuel outputs are to be utilised.

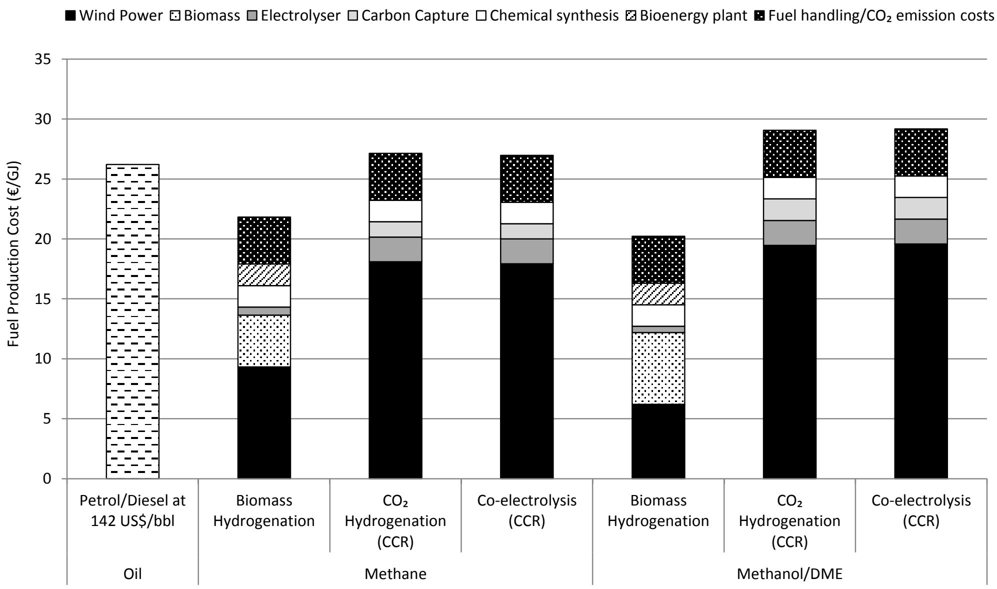

Figure 31. Fuel production costs for electrofuel pathways for gaseous and liquid fuel output in 2050.

It can be seen that the CO_2 electrofuels have no biomass expense, which suggests that there are renewable transport pathways that eliminate biomass for fuel production and that still can be competitive with petrol when associated CO_2 emission costs are accounted. This is the most striking result to emerge from the data used, indicating that electrofuels could be competitive with fossil fuels. As the fuel production price has a cost breakdown, it can be used as an indication that some pathways are more sensitive to the biomass resource price, bioenergy plant investments in the case of bioethanol, and biogas production, while electrofuels are most sensitive to the electrolysers and wind investments. This highlights that these prices are strictly indicative, as they are based on the certain price prediction of resources and technologies.

Figure 32 shows the correlation between biomass consumption and fuel output, which confirms that the conventional biofuel pathways are very biomass-intensive. It is important to note that even in cases where biomass is to be used as the resource for fuel production, by using bioelectrofuel it is possible to reduce the demand for what is likely to be a limited biomass resource in the future.

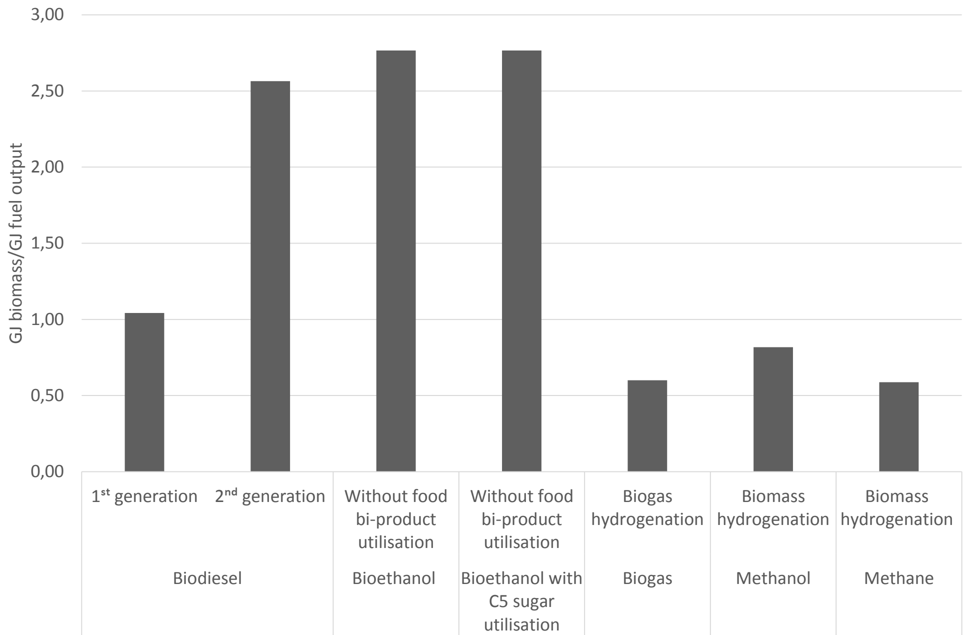

Figure 32. Biomass consumption per fuel output for the scenarios that use biomass as a resource

7.3.3 Short conclusion

The results of energy and cost comparison suggest that there are several options that could be used as transport fuel in the future. The electrification is the most efficient method from an energy point of view. In cases where energy-dense fuels are necessary, such as for freight transport, methanol/DME seems to be a more attractive option than methane. The production of methanol/DME is cheaper than the production of methane with electrofuel pathways when the infrastructure costs are considered. The strict distinction of using liquid or gaseous fuel in the future cannot be made, as it was seen that the results vary depending on the data used, especially engine efficiency data. The electrofuel pathways are the most resource-efficient, and even the bioelectrofuel shows rather high improvement in needed resources for the same fuel output compared to other bioenergy-based pathways. The decisive factors for a fuel mix deployed in the future will depend on the amount of affordable bioenergy in comparison to the levelised costs of electricity from wind, as electrofuels are utilising electricity for fuel production, technological development, demonstration of facilities on a large scale, and the infrastructure costs.

7.4 ANALYSES LIMITATIONS

Given that the focus of the study was to analyse different fuel pathways with technological change over 40 years, it is not inconceivable that dissimilar results would have arisen if the focus were on upcoming years. As with any analysis that includes technology and cost forecasting, many uncertainties are inevitable as the knowledge on future development is based on the current predictions. This means that used data may not necessarily represent what will be possible in the future, and future studies are therefore needed in order to validate the data assumptions. However, it is important to evaluate what could be potential solutions for the future, as the investments in both the energy and transport sectors are time- and cost-intensive and investments made today will have a long-term effect on the system. The major analyses limitations are summarised below.

The cost estimations are the most significant uncertainty in all presented analyses. The costs of the technologies that are still at the research and development level, such as electrolysers (SOEC), are very uncertain and completely dependent on technological development. However, the costs of other technologies that were part of the analysis are also subjected to changes and need to be taken with certain caution. Nevertheless, the expected use of these fuels is in the future. More precisely, the fuels are analysed as part of a 100% renewable energy system in 2050; thus, there is enough time left to gain more detailed knowledge on technology development.

The gathered technical data on SOEC, such as efficiencies and predicted development, was confirmed by a developing institution [262], so it is assumed that the data is as certain as it can be at the current research and development level. However, at the final stage of study it was revealed that these electrolysers have been implemented in the demonstration project. This means that the data validation could be carried out in future work with data from the demonstration plant. Furthermore, as analyses were based on the energy balances, which were created from stoichiometric reactions, the alteration of energy densities of certain components could cause differences in the results. The conversion losses between production cycle elements are currently unclear, as the data of some of the proposed pathways is not available. In order to account for potential shortfalls in the approach, additional losses are subtracted in the production process to better reflect the reality. These limitations underline the difficulty of collecting secondary data that can be used for this type of analysis.

The vehicle and infrastructure costs are included in the first study presented in Section 7.1, but they are not part of the fuel production cost estimates identified in Section 7.3. However, the fuel production costs include the fuel handling costs and system balancing costs as they are calculated through the energy system analysis tool. This is primarily due to the idea of calculating the fuel production costs and not the costs of deploying the individual pathways, which was done in the first analysis. The vehicle efficiencies were based on the current data available on predictions for 2030, and no changes for 2050 were assumed. In the future, more details will be needed to assure better accuracy of the results. As all of the analyses were energy system analysis, the model was calibrated so that the integration of needed wind capacities was balanced by installed electrolyser and storage capacities. Unfortunately, it was not possible to investigate in detail the synergies that can be exploited between production cycle elements, but some of the synergies that could be used within the production cycle are indicated.

Nevertheless, all results provide essential information on pathway creation and the production cycle elements. Furthermore, they highlight the types of technologies that will be important in the context of 100% renewable energy systems, as well as the basis for further development of the electrofuel pathways. The work carried out could be the springboard for more detailed analysis of electrofuels as part of the energy system, the optimisation of operation strategies for production plants, analysis of how to maximise the synergies between specific elements of the production cycle, and the plan for deployment of electrofuels in the transport sector.

8 PUBLIC REGULATION OF ALTERNATIVE FUELS

The implementation of new technologies is a challenging task from the public regulation perspective. The political phase of technological change can be diverse, as it can be expected that every radical technological change will meet resistance from established actors and institutions. The choice awareness of different alternatives in the EU was discussed in Chapter 3 and it is going to be further analysed here, with a stronger focus on policy development. The reason why the EU is chosen concerns the consequences of EU decisions on Member States, e.g. Denmark. This chapter presents the historical development of the EU alternative fuel policies, starting with an introduction of the main actors involved in policy creation, and continuing with the political agenda from the 2000s until today, while highlighting the technologies that are leading the agenda. The chapter finishes with the implication of the current legislation on electrofuels.

8.1 EUROPEAN UNION AND OTHER INFLUENTIAL ACTORS IN THE LEGISLATIVE PROCEDURE

In order to understand how the policies were created, it is important to get an overview of the main actors involved. The EU institutional setting defines the policies on alternative fuels through different actors. The main actors involved – European Commission, European Parliament, and Council of the European Union (the Council) – and two advisory bodies (European Economic and Social Committee, and Committee of the Regions) will be further described below, with their power roles in legislative decision making being outlined. The main three institutions that are involved in the EU legislations are the Commission, the Parliament, and the Council. The roles of the Court of Justice, the Court of Auditors, and the European Central Bank will not be touched upon.

The *European Commission* is the executive body of the EU. It is a leading policies and legislation entrepreneur as it has a sole right of initiating and presenting a proposal for a legislation to the Parliament and the Council. The Commission may be asked to draft the proposal by the Council, European Parliament, and citizens of Member States according to the Treaty of Lisbon [263]. The Commission is the target for interest groups, stakeholders and anyone that has the will to influence policy creation, as it is the policy agenda setter. The Commission also monitors the observance and application of legislation in the Member States, administrates and implements Union legislation, and represents the EU in international organisations [264]. Together with the Court of Justice, it is enforcing EU law. The Commission has 28 members, including the President and Vice-Presidents, called commissioners. As an institution, the Commission has employed staff who are organised into Directorates-General (DGs), which are divided by their policy activity and named after the latter.

The *European Parliament's* role in the European Union legislation has increased over time. In the early years of the EU, the Parliament had only a marginal role in the policy process, but this changed by the Treaty of Amsterdam [265]. Nowadays, the Parliament has a co-decision role (alongside the Council) over the EU budget and nearly all legislation. Without the agreement between the Council and the European Parliament, legislation cannot be passed [264]; in some cases, with an absolute majority, the Parliament can reject the legislation. The Parliament monitors the use of funds and has supervisory powers over the Commission. With a majority of its component members, the Parliament can ask the Commission to submit legislative proposals. The Parliament is the only directly elected institution of the EU, elected by the citizens of the European Union. It consists of 751 members currently divided into seven political groups [266].

The *Council of the European Union (the Council, the Council of Ministers)* is a central legislative and decision-making body [267] that should not be mistaken for the *European Council* [268]. The Council has the co-decision (with the Parliament) in the ordinary legislative procedure, and it establishes the budget (which has to be approved by the Parliament). The Council will often indicate to the Commission the desired legislation to be drafted. There are no fixed members of the Council, as each country sends the minister of the policy field that is on the agenda. This results in 10 different formations of the Council, depending on the topic of discussion. The Council, with a simple majority, can request that the Commission carry out studies and submit a legislative proposal accordingly. The Council is supported by the Permanent Representatives Committee (COREPER) and more than 150 'Council preparatory bodies'. These working parties and committees examine the Commission's proposals and conduct studies necessary for forming the Council's decisions. The more detailed tasks of the Council can be found in [264,267]. In the special legislative procedures, the Council is acting like the sole legislator, while the Parliament needs to give its consent to the proposal or be consulted on it [269]. The Member States' interests are promoted in the Council and, therefore, the influence of more powerful Member States can potentially influence the Council's decisions and choices.

Two advisory bodies that were engaged within alternative fuel directives do not have legislative power but have the consulting role. The European Parliament, the Council, and the Commission may consult them and/or they may initiate their opinions on their own initiative. The *European Economic and Social Committee (EESC)* is appointed by the Council. It consists of a maximum of 350 advisors of the most representative organisations in Member States. It can be seen as a bridge between Europe and organised civil society (employers, workers and various interests). The *Committee of the Regions (CoR)* was established in 1994 in order to bring the citizens closer to the EU through authority representatives, as most of the European legislation has a direct regional or local impact. The CoR is appointed by the Council and it consists of a maximum of 350 members of regional and local authorities. The CoR needs to be consulted by the Parliament and the

Council in the ordinary legislative procedure for different areas, such as transport, the environment, and climate change. The CoR and EESC must be consulted on a large number of areas, including energy infrastructure, the environment, and transport. The Council can also consult the CoR regularly in connection with different draft legislation [264].

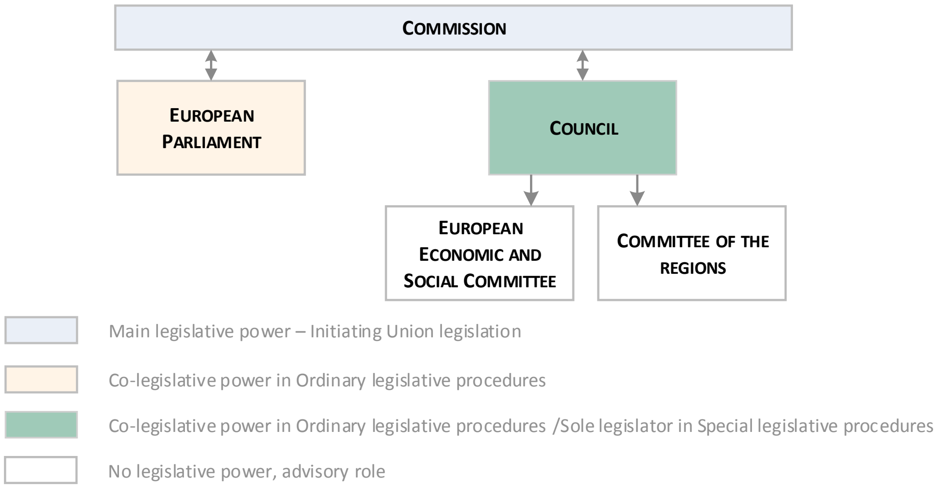

Figure 33. Power roles in the legislative procedure

The power roles in the legislative procedure of the EU actors are outlined in Figure 33. The Committees are presented under the Council as they are appointed by it; however, their opinion is forwarded to all three main bodies.

8.1.1 Commission expert groups

The Commission calls for external expertise in order to bring scientific and practical knowledge to policy decision making. This can be done by creating expert groups or external consultants. There are formal and informal expert groups, depending on whether they are set up by the Commission or an individual department within the Commission. The Commission does not appoint external consultants, but they are financed and administrated by the Commission. Expert groups and external consultants are listed in the register [270]. The roles of the expert groups are to advise and provide expertise to the Commission on the preparation of the proposal and policy initiatives, delegated acts, and coordination and cooperation with Member States and stakeholders within the implementation of the legislation. The input of the expert group is not binding on the Commission and DGs, meaning that the final proposal from the Commission does not necessarily have to include the input given by the expert groups. The following are some of the expert groups involved in alternative fuels: the European Expert Group on Future Transport Fuels (industrial stakeholders and civil society); the Joint Expert Group on Transport and Environment (MS representatives); the Competitive Automotive Regulatory System for the 21st Century (CARS21); the Biofuels Research

Advisory Council (BIOFRAC); and the European Biofuels Technology Platform (EBTP).

8.1.2 Interest groups role

Non-governmental organisations (NGOs) can contribute to the energy and environmental legislative decision-making process by participating in the consultations and debates. The opinions of the interest groups are generally welcomed by the politicians in the policymaking process as they provide information from the actors that are affected by the policies. As stated by Wallace *et al.*, the policy is more likely to be effective if the affected actors are involved in the process [265].

The NGOs can influence the decision making of the Commission, the Council and the Parliament by engaging in different tasks and events [271]. A short summary of potential engaging mechanisms is stated in the following text. In order to engage with the Commission, NGOs need to participate in stakeholders' thematic consultations, online consultations, and debates organised by the EC, involving EC activities such as "European Green Week" and reporting the practices that violate rights to the Commission. The Council can be influenced by sending a reaction letter or manifesto about the decisions made by the Council; however, this usually needs to be done by the network of NGOs in order to send a strong message. To engage with the European Parliament, NGOs can exercise the right of petition before the Parliament, through the citizens' enquiry service unit or by participating in Citizens' Agora.

The following are the main NGOs that were/are involved in alternative fuel policies: Friends of the Earth (FoE), Greenpeace, ActionAid, BirdLife International, ClientEarth, the European Environmental Bureau, FERN, Transport&Environment, and Wetlands International. The NGOs have been actively involved in requesting more transparency within the alternative policies, especially within biofuels. In 2010, ClientEarth, Transport&Environment, the European Environmental Bureau, and BirdLife International sued the European Union. The claim challenged "*the Commission's failure to release documents containing previously undisclosed information on the negative climate impacts of widespread biofuels use in the European Union*" [272]. Furthermore, in May 2011, ClientEarth, Friends of the Earth Europe, FERN, and the Corporate Europe Observatory (CEO) filed a lawsuit against the Commission for the lack of transparency on biofuels policy [273].

8.2 POLICIES WITHIN ALTERNATIVE AND RENEWABLE FUELS

Transport has raised political and research attention during the last two decades, mainly due to the high dependence on oil products and questionable security of supply in the future. This section focuses on the decision making that imposed biofuels as a main solution for the transport sector, and will look into implications of existing policies on electrofuels. Finally, a map of identified actors involved within electrofuel production is presented. Figure 34 summarises a list of proposals and policies related to biofuels and alternative fuels that were included in the discussion.

COM (2001) 547 final	Proposal for Directive on the promotion of the use of biofuels for transport
2003/30/EC	The Directive on the promotion of the use of biofuels or other renewable fuels for transport
2003/96/EC	Energy Taxation Directive (Article 15 and 16)
COM (2005) 628 final	Biomass action plan
COM (2005) 634 final	Promotion of clean road transport vehicles
COM (2006) 34 final	An EU Strategy for Biofuels
2009/33/EC	The Directive on the promotion of clean and energy-efficient road transport vehicle
2009/28/EC	Renewable Energy Directive (Repealing of Directive 2003/30/EC)
COM(2010) 186 final	A European strategy on clean and energy efficient vehicles
COM(2012) 595 final	Proposal for a Directive of the European Parliament and of the Council amending Directive 98/70/EC relating to the quality of petrol and diesel fuels and amending Directive 2009/28/EC on the promotion of the use of energy from renewable sources
COM (2013) 17 final	Clean Power for Transport: A European alternative fuels strategy
COM(2013) 18 final	Proposal for Directive on the deployment of alternative fuels infrastructure
2014/94/EU	The Directive on the deployment of alternative fuels infrastructure
COM (2014) 15 final	A policy framework for climate and energy in the period from 2020 to 2030

Figure 34. List of proposals and policies relating to alternative fuels

8.2.1 Political process behind alternative fuel policies

Even though the first legislation that introduced biofuels in the EU was in 1985, the ambitious promotion of biofuels started in the 2000s, when climate change gained political interest. Prior to the 2000s, biofuels were mostly mentioned in the context of energy security. During the 1990s, powerful Member States such as France led the biofuels agenda in the EU, based on their strong agricultural and industrial sectors [274]. This was also a rather chaotic period, as the Member States had the freedom to apply exemptions or reduced rates to biofuels, whereby creating many diverging interpretations of the same legislation [275]. At the end of the 1990s, the Kyoto protocol introduced the environmental concerns, which eventually resulted in environmental concerns being more important for biofuels promotion than previous concerns of energy security. In 2000, the Commission set up the European Climate Change Programme (ECCP) in order to establish security of supply and to find a way in which to meet the Kyoto emission targets. At the time, Europe was not progressing well on GHG emission targets set up by the Kyoto protocol, which was not satisfactory as the European Union aimed at being a leader in climate policies [64]. Based on the ECCP input, in 2001 the Commission put forward a communication. It included a proposal for a directive on the promotion of the use of biofuels for transport [81]. The communication included an overview of the alternative options in which electric vehicles did not seem a promising candidate for high-volume marketable vehicles, while the Commission stated that the development of methanol and DME as alternative fuels would be monitored. Even though the communication identified hydrogen and natural gas as potential alternative fuels, the proposal included only biologically based fuels. It was clearly stated in the proposal that biofuels are desired from a political point of view, due to their beneficial outcomes: emission reduction, security of supply, and income source for the agricultural sector, which reflected the main drives of the energy challenge:

> *"There is no doubt that promotion of the use of biofuels in the EU is desired at political level for the reasons of sustainable development, CO_2 reduction, security of supply and the additional positive influence on rural development and agriculture policy."* [81]

This threefold approach brought more complexity into the policy structure, as this added more concerns that had to be addressed and, as such, turned the policy more vulnerable to changes. In the proposal, the biofuel targets were mandatory, as it was believed that the simplest way of promoting biofuels in the long term would be obligatory blending with fossil fuels:

> *"Member States shall ensure that the minimum proportion of biofuels sold on their markets is 2%, calculated on the basis of energy content, of all gasoline and diesel sold for transport purposes on their markets…"*

The targets were set at 2% in 2005 and 5.75% in 2010, of which 1.75% should be in the blended form [81]. At that point, around 10% of Europe's agricultural land was set aside due to food overproduction. The 5.75% target was estimated as a quantity that could be produced on the set-aside land by growing energy crops [276]. The proposal not only overlooked other alternative options, but also focused merely on practical issues of introducing biofuels from an institutional point of view. The mandatory targets provided a stable car sales market and secured the investment in that period. Interestingly, there was no environmental focus in the proposal, just the indication that there are environmental benefits. With this approach, it disregarded the potential risk for the environment and human health:

"*Apart from the obvious CO_2 reduction advantage, any other environmental effects would appear to be insignificant, either positive or negative providing a proper implementation…*" [81]

This was identified as a risk-indifferent approach by Di Lucia [80], as the potential environmental issues and negative impacts of biofuel implementation were overlooked, assuming that biofuels are carbon-neutral and can be sustainably produced. There being no environmental focus or evaluation as such was one of the main criticisms from the Parliament, alongside that the directive should not rule out the other alternative fuels in the sector. The Council (as the representative of the Member States) changed the mandatory targets into indicative targets, and enabled the Member States to choose the suitable fuels for their national markets. This input was based on the different interests of the Member States in how to develop the EU policy, as their potential and interest in feedstock production and biofuel consumption were different according to Wiesenthal *et al.* [274]. Finally, the directive on the promotion of the use of biofuels or other renewable fuels for transport was adopted in 2003 [27]. Even though the directive's title includes the promotion of other renewable fuels, in the text of the directive there is no clear list of other possible alternative fuels. The only alternative fuels mentioned are LPG and CNG, which are obviously not renewable options, and hydrogen as a potentially renewable option. The directive clearly promoted biofuels as the primary option, while the other alternatives were only mentioned.

The promotion of biofuels was further supported by the Energy Taxation Directive [277], enabling a tax reduction on biofuels and, through this, reducing the cost gap between the fossil fuels and biofuels. This was one of the main promotional instruments that was successful according to Pelkmans [278], as taxation has been indicated as the only tool that can levelise the high production costs of biofuels with the fossil fuel costs. Today the obligation schemes are more commonly used, as the tax exemption schemes resulted in revenue losses for Member States [278].

As the Member States did not reach the targets set up by the directive in the following period, it was doubted that the Commission's proposal for mandatory targets was the best way in which to engage the Member States. In 2005, the Commission turned to several industry-dominated bodies in order to shape a new proposal for alternative fuel policies. The Commission's Directorate-General for Research created the *Biofuels Research Advisory Council* (BIOFRAC), which was effectively a pro-biofuels lobby with the mission to ensure a breakthrough of biofuels and to increase their deployment in the EU, which was reported in the report "*Biofuels in the European Union: A vision for 2030 and beyond*" [279]. This Council included major European biofuel stakeholders, such as the biofuels and oil industry, car producers, agro-, forestry and food industry, and research institutes. The BIOFRAC also had a responsibility to provide input for the FP7 Programme in the period of 2007 to 2013, which supported the funding for biofuel research and development. In the same year, the Commission established the *Competitive Automotive Regulatory System for the 21st Century* (CARS21), with key automotive stakeholders that delivered a report in 2006 which encouraged the development of biofuel policies [280]. In 2006, the *European Biofuels Technology Platform* (EBTP) was established with the Steering Committee, which more or less mirrors the BIOFRAC representatives, representing one more pro-biofuel lobby. The relations of the created bodies towards the European Commission are shown in Figure 35.

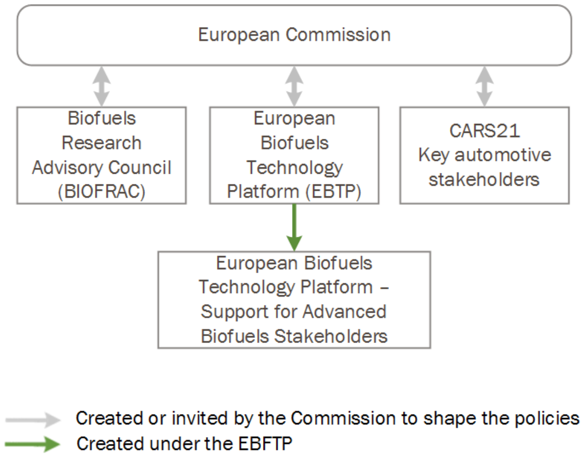

Figure 35. European Commission platform for biofuel development

It could be argued that the Commission, by choosing this pallet of board members in the BIOFRAC, EBTP and CARS21, whereby representing the corporations that were facing the economic crisis and that had a focus on finding stability for the companies, have guided the policies that are not necessarily the best sustainable option for future development. By having the main stakeholders directly involved in policy creation, some targets are adjusted to their needs, which could create an economic lock-in [82].

In 2005, the Biomass Action Plan was communicated by the Commission, and announced the possible revisions of the Biofuels Directive based on the report that assessed national targets and schemes for sustainability requirements [281]. The Biomass Action Plan also included ANNEX 12 – The Commission's perspective on biomass and biofuel research, which set up the research priority of the Seventh RTD Framework Programme and Intelligent Energy for widespread market deployment of biofuel technologies. At the end of 2005, the Commission presented the proposal for the directive on the promotion of clean road transport vehicles, with an aim to reduce pollutant emissions by the transport sector and to establish a market for clean vehicles [282].

In 2009, the "energy and climate package" was set up including two directives, of which the Renewable Energy Directive (RED) repealed the Biofuels Directive with two major changes. Compared to the Biofuels Directive, the RED includes the sustainability criteria for biofuel production, with the indicative targets being changed into mandatory national targets. With this directive, biofuels were again given the priority in front of other alternatives, and the strong promotion is obvious by using the same wording from the Commission's proposal for the first directive: *"Member States shall ensure"*. Interestingly, the RED was accepted after the first reading, which was not the case with Directive 2003/30/EC, although the mandatory targets were increased to 10%. However, the RED did not go through as a conflict-free directive, even though the Parliament, the Council and the Commission were aligned. Neglecting the non-reached goals from previous years and debatable sustainability of the 10% target, the RED has raised a lot of internal and public debate.

The Committee of the Regions (CoR) and the European Economic and Social Committee (EESC) did not agree that biofuels were the best substitution for fossil fuels, and pointed out that renewable electricity is a much better choice [275]. Not only that, the consultative committees were disagreeing with the Commission, but the public concern and the environmental NGOs opposed the 10% target unless the sustainability criteria were stronger [12]. During the debate about the RED, several reports by prominent international organisations were published, raising issues on food security and sustainability of the production due to the 10% targets [71,100,283,284]. Neither inside nor outside disagreements influenced the set-up target in the RED, but the policy was shaped to include the sustainability measures of biofuels, though they were doubted as weak [285]. While the sustainability criteria included the environmental concerns of the biofuels, including the GHG reduction requirement, with some of the biofuels counting as double the GHG savings [13], the social concerns of biofuels were not set up as obligatory. This is striking as the food prices in the period of biofuels implementation were raised significantly [286]. Even with the Parliamentary committee arguing for the mandatory social criteria, the Commission rejected this inclusion as the criteria were difficult to verify and would intervene with WTO trade rules [24]. The social concerns were addressed in the RED through voluntary schemes and bi-annual reporting requirement [13]. In the period between 2008 and 2011, the literature was strongly divided into two groups: one arguing that the rise in food prices was not a direct outcome of biofuel consumption, and the other one arguing for [287]. As one of the greatest social concerns of these transport fuel policies, the debate on "fuel versus food" is still ongoing.

The tendency of neglecting common scientific knowledge on environmental and social impact has occurred in policymaking. In their book, Giampietro and Mayumi [82] discuss the delusions about biofuels as a promising replacement for fossil fuels. The criticism of biofuel sustainability continued to grow and the heightened requirement for policy changes was strengthened after the implementation of the RED. The discussions of the surrounding community, mostly focusing on Indirect Land-Use Changes (ILUC), led the Commission to include these measures in the new policy. The Commission invited the International Food Policy and Research Institute (IFPRI) to carry out the study on ILUC in order to back up the 10% target [98]. The optimistic assumptions of this study, according to Levidow [12], led the environmental NGOs to oppose the study and criticise the Commission for disregarding the carbon debt caused by using the biofuels and focusing only on direct land changes. With the IEEP report [100] as a reference of the total GHG emissions caused by biofuels, nine NGOs questioned the 10% target of the RED and demanded inclusion of ILUC in the sustainability criteria [12].

In 2009, the directive on the promotion of clean and energy-efficient road transport vehicles was released [288], with the aim to stimulate the market for clean and energy-efficient road transport vehicles; however, no specific alternatives were stated. In 2010 the Commission issued an indecisive report on ILUC [289] which favoured the investment incentives in any regulatory criteria and proposed three medium-term choices, of which the GHG penalty option on some biofuels provoked biodiesel investors. At the end of April 2010, the Commission published a communication – European strategy on clean and energy-efficient vehicles – that set up a new industrial approach towards clean and energy-efficient vehicles in order to establish an internal market and new jobs [290]. The strategy also aimed to establish the European automotive industry as a global leader in alternative propulsion technology. The strategy recognises alternative fuels for combustion engines, including liquid biofuels and gaseous fuels (including LPG, CNG and biogas), electric vehicles and hydrogen fuel cell vehicles.

Finally, in 2012, the Commission issued a proposal for modifying the Fuel Quality Directive and Renewable Energy Directive [291] to include the emissions from the indirect land use changes (ILUC) and to disincentivise the first-generation biofuels. The political agreement between the Council, the Parliament and the Commission was reached in June 2014 after more than two years of debates [292]. During the debate over the ILUC factor as an environmental measure, the Commission issued a proposal for a policy framework for climate and energy in the period from 2020 to 2030 in January 2014 [86]. The proposal included three key statements: the need for improved biomass policy; no public support for first-generation biofuels; and no decarbonisation targets for transport fuels. The latter is obviously clashing with the current policy, which perhaps resulted from the controversies surrounding biofuel and the pressure on the Commission:

> *"The Commission does not think it is appropriate to establish new targets for renewable energy or the greenhouse gas intensity of fuels used in the transport sector or any other sub-sector after 2020."*

This statement is concerning as it downsizes the problem of decarbonisation of the transport sector after 2020. Led by the Commission's statement, the Council suggested that the Commission revise their conclusion:

> *"The European Council therefore invites the Commission to further examine instruments and measures for a comprehensive and technology neutral approach for the promotion of emissions reduction and energy efficiency in transport, for electric transportation and for renewable energy sources in transport also after 2020."* [293]

At the same time, after more than a decade, the Commission finally acknowledges, based on the proposal for alternative fuels strategy [14], the need for other alternative fuels than biofuels:

> *"Based on the consultation of stakeholders and national experts, (…) electricity, hydrogen, biofuels, natural gas, and liquefied petroleum gas (LPG) were identified as currently the principal alternative fuels with a potential for long-term oil substitution…"* [28]

This is an important step; however, biofuels are still the only supported renewable liquid fuel alternative. Natural gas and liquefied petroleum gas could be an intermediate solution for the transition from oil; however, they are not suitable for systems based on renewable energy and should not be perceived as a long-term solution. Hydrogen and electricity are efficient alternatives for transport (see Chapter 7) and can be used in renewable energy systems, if the resources used for their production are renewable. An incentive for implementing the mentioned alternative fuels has arrived with the directive on the deployment of alternative fuel infrastructure at the end of 2014 [28]. This directive requires the Member States to develop national policy frameworks for the market and infrastructure development of electricity, LNG, CNG and hydrogen in the period of the next two years. This requirement can be seen as a good start for diversifying the options for transport, and also can be useful for electrofuels with methane as an end fuel, as the infrastructure should be developed through the enforcement of this directive. Moreover, the final conclusion of the Indirect Land-Use Changes (ILUC) discussion acknowledges electric vehicles on renewable energy with a multiplying factor of five [85]. These two incentives will potentially break a vicious circle of infrastructure issues across EU borders and push renewable fuels in the transport sector.

8.3 IMPLICATION OF EXISTING POLICIES ON ELECTROFUELS

Until today, electrofuels were not promoted as such within the alternative fuel policies. This could be due to the fact that most of the legislation on alternative fuels was published before the demonstration of this technology. The first electrofuel facility has been operating in Iceland since the end of 2012, and has been successfully producing methanol from carbon dioxide emissions and with hydrogen from water electrolysis [41]. Therefore, the modifications and new directives published during the last three years could have assessed these fuels as a potential alternative for the transport sector.

However, as this was not the case, the interpretation of the policies currently in place and their implication on electrofuels are going to be assessed.

As electrofuels have a high share of electricity in the production process, due to their aim to convert electricity into storable chemical energy, the origin of electricity is an important aspect of these fuels. According to Directive 2009/28/EC [13], only fuels produced by 100% renewable energy can be acknowledge as renewable fuels. This implies that only electrofuels that use renewable electricity and additional renewable resources needed for the production cycle can be accounted as renewable fuels. From today's perspective, this can potentially hinder the technological development, as currently there are no specific incentives for producing these fuels, because they are not recognised as alternatives or renewable fuels. In the long term or when strictly talking about systems with a high share of renewable energy sources, this is not problematic; however, it could have consequences on the near-term development, demonstration and deployment of these fuels. It is important to separate the bioelectrofuels and CO_2 electrofuels for one specific reason, as the first uses biomass as a resource, which is supporting renewable resources. When considering bioelectrofuels, if electricity is coming from renewable resources, they can be accounted as renewable. However, when considering CO_2 electrofuels, due to the emissions, the situation is more complex. The recycling of carbon dioxide (CCR) or carbon dioxide utilisation (CDU) is not recognised as CO_2 reduction, nor is it recognised by monitoring or reporting regulations of the Emission Trading Scheme (ETS) [91]. Recycling of carbon dioxide is also not recognised as carbon-neutral according to IPCC [169]. Implementing CDU into policies should be done carefully, as it can be difficult to regulate the balance of the emissions if they are converted into new products, which potentially affects the emissions of another sector. However, the positive effect on climate mitigation should be assessed by life cycle analysis (LCA) of these fuels and the legislation can be adapted accordingly.

Secondly, the Fuel Quality Directive (FQD) [92] puts restrictions on suggested liquid fuel outputs methanol and DME. According to this directive, methanol and DME are recognised as oxygenates for petrol and can be blended up to a maximum of 3% and 22%, respectively, of the total volume. This could be the reason for the low presence of these fuels in the transport sector. When it comes to the infrastructure changes, including vehicles, there are no subsidies of converting vehicles or filling stations to methanol or DME. This is, of course, understandable for the current situations, as there are no high blends or pure fuel available on the market. The restricted blends in place do not require vehicle alteration and, therefore, cannot be seen as a supportive means for a higher market share of these fuels. The new directive on the deployment of alternative fuel infrastructure [28] could have a positive impact on future deployment of electrofuels, as it imposes the application of infrastructure for CNG, which can be used for methane produced by an electrofuel process.

9 ROADMAP FOR ELECTROFUELS IN FUTURE ENERGY SYSTEMS

It is difficult to give specific public regulation recommendations, as technological change over 40 years is being assessed. Furthermore, there are many uncertainties within the development of certain technologies needed for the production of these fuels, e.g. whether they will be able to reach their technical expectations and whether they will be economically feasible. It is also believed that the institutional setting and policy development will go through radical changes over this period of time. Therefore, a short roadmap is presented instead of specific policy recommendations to get an overview of the needed steps for deployment of electrofuels.

As electrofuels are anticipated to be part of the 100% renewable energy system, the technologies used for fuel production are important in the context of this type of system. This fuel production concept has not be proven yet on a large scale, due to the current technological development of the production cycle components. There is a limited amount of technology developers of electrofuels as a combined concept, meaning that the competition is not high. A similar situation is seen in the singular technology market of biomass gasification and electrolysis, but certain progress has been noted in recent years. However, this does not entail that these types of fuels have not been demonstrated; rather, due to the current EU regulations, they are not entitled to be renewable fuels if the electricity for fuel production is not renewable. This could potentially hamper the development of the technology until the share of renewable resources in the system is not high enough. The electrofuels should be seen as a long-term solution for the transport sector, so it is important to support technological development in order to integrate wind power and other fluctuating resources in the heavy-duty transport sector and to reach the goal of a 100% renewable energy system.

In order to be able to utilise electrofuel in the transport sector, the key is to develop the production process and individual components. There should be a long-term plan of funding in order to support the research, development and demonstration of biomass gasification and electrolyser technologies. It is important that funds are earmarked for electrofuels as this will support the development of singular technologies. The funding opportunities will open the way for commercialisation of this technology; therefore, this step is seen as important. On the European Union level, there are many funding opportunities, e.g. Horizon 2020, which is the EU Framework Programme for Research and Innovation that started in 2014 and will run until 2020; the Competitiveness and Innovation Framework Programme (CIP); and European Structural and Investment Funds. Horizon 2020 is the biggest fund ever launched by the EU. It has a budget of €80 billion [294] and it has recently granted a project of electrofuel production [46]. The Danish Government has dedicated funds for transition to a 100% renewable system

[295]. Moreover, the EUDP (*in English* – Energy Technology Development and Demonstration Programme) is a Danish funding programme that supports new technologies that can create jobs, increase security of supply, and contribute towards making Denmark fossil-free in 2050 [296]. There are national and EU funding opportunities that could be used for developing, testing and demonstrating biomass gasification, electrolyser and CO_2 recycling technology. The largest dedicated funding programme for innovative low-carbon energy demonstration projects is called NER 300 [297], which is a good funding opportunity for demonstrating electrofuel production. Further funding will be given to projects after 2018, and in October 2014, the EU agreed to create NER 400 [298]. This type of funding and technology demonstration would enable knowledge and experience exchange, which would ease up further technological development needed before the technology could be introduced to the market. The development and commercialisation of each step of electrofuel production will enable the large-scale implementation of electrofuel production facilities.

Deployment of electrofuels and related technologies can be seen as very important for Denmark, as there are already research institutions and industrial producers that are associated with this. High-temperature electrolysers SOECs have been both researched and demonstrated in Denmark by Haldor Topsøe A/S and the Technical University of Denmark (DTU) [262]. There have been previous projects that have tested and analysed the integration of SOEC [299,300], and as part of the ongoing El-Upgraded Biogas project the facility with the SOEC device should be designed, demonstrated and tested by Haldor Topsøe [301]. Denmark also has experience with biomass gasification [122]. Therefore, it is important that research, demonstration and commercialisation of these technologies continue, as this could establish Denmark as an important actor in electrofuel production and offer new job opportunities.

As electrofuels combine different technologies for fuel production, it could be said that the funding opportunities and policies will be spread around different topics. The joint approach that will look at electrofuels as one technology could potentially be beneficial for the development and commercialisation of these fuels. However, it can be seen from the Icelandic example that the projects can be established without public funding, if the projects are seen as economically viable. It was discussed previously that existing policies do not specifically promote this type of fuel, but the idea behind the renewable policies is in line with the production of electrofuels. Certain promotions of recycling the carbon dioxide rather than storing it have already arisen, which will consequently help the development of electrofuels for mobility. However, there is a need for understanding overall how these fuels and their production cycle components could benefit the already set-up policy targets. It is important that the policies are developed without inhibiting other alternatives that could support climate mitigation, security of supply, and job opportunities. The support for technology development from both researchers and politicians is favourable and can create special market conditions to enable these technologies to compete within the existing market conditions. As these technologies are used for producing renewable fuels that will have both environmental benefit and the integration of more renewable technologies, support in terms of fix subsidies could speed up the distribution. Accounting that some of these fuels can be utilised in the existing infrastructure with small alteration, once they reach the market, further use should not have major technical limitations. Currently, the use of alcohol and ether fuels is restricted to low fuel blends with petrol; therefore, supportive legislation that will enable the use of higher alcohol/ether blends as a transition stage to the support of pure alcohol/ether fuels is necessary. This will enable the deployment of these fuels and initiate putting in place the filling infrastructure needed for successful supply. This will increase the market potential for alcohol/ether fuels. Subsidies for engine conversion to these types of fuels should be provided in order to attract the consumers to convert their vehicles. Moreover, even though some of the fuels can be used in converted vehicles, there is an opportunity for a new vehicle market for dedicated vehicles for alcohol fuels and gaseous fuels. Overall, there is a need for further demonstration of vehicle performances running on methanol or DME, as there are indications that they could improve the performances of alternated petrol and diesel vehicles. Currently the mandatory targets can be met by suggested biofuels, but in the long run this will not be an option and other renewable alternatives will have to be promoted.

The electrofuel development needs to be pushed by the R&D and demonstration as an initial phase, creating communities or dedicated funds that will enable their development, but the need for these fuels in the future will potentially shape the policy support. The development of electrofuels will eventually depend on how much the market and political agenda are in resistance of change, but if all arguments are taken together, the technology is being perceived as beneficial for the environment and as a storage agent for renewable energy; the creation of legislative support for these fuels can be successful. The European Union should use the benefit of having this technology already demonstrated and developed within the EU borders, and convert this niche market into a mass market, which could eventually establish the European Union as a leading actor in the competitive race for global fuel security.

9.1 SUMMARY OF ROADMAP RECOMMENDATIONS

The following recommendations could play an important role in establishing electrofuels as transport fuels of the future. The recommendations are grouped according to their focus:

RELATED ACTIVITIES TO RESEARCH, DEVELOPMENT AND DEMONSTRATION

- **Intensify research, development and demonstration within key technologies for electrofuels**

  The R&D activities need to be increased especially for electrofuel production by integrating fluctuating electricity through electrolysis. As some of the technologies for production are at different technological stages, the needed activities will differ. The activities in research and development of high-temperature electrolysis as a central part of the electrofuel production cycle are important in order to improve the durability of the cells and integration with other components of the production cycle. Alkaline electrolysis as a commercialised technology should be supported for the demonstration of electrofuels until the SOECs reach higher development stages. Development of gasifiers for different types of biomass feedstocks, especially for non-homogeneous residual biomass, should be supported, as future energy systems will have to maximise the use of available biomass to meet all demands in the system. The scaling-up of already developed technologies is necessary to eliminate operating problems and to lower the technology prices. Carbon recycling from stationary sources is already developed; however, air capturing is not fully developed and further research is needed before demonstrating the use of this technology.

- **Intensify demonstration of electrofuels in different transport modes**

  Development and testing of vehicles for methanol and DME should be supported in order to generate knowledge on vehicle performance. Performing tests with different driving cycles will show the efficiencies of vehicles running on these fuels. Furthermore, the testing of deployment of electrofuels in marine and aviation industries in comparable field demonstrations, in order to determine the performance of engines compared to primary fuels used, is a first step in introducing the wider use of electrofuels.

- **Provide more funding opportunities for research, development and demonstration**

  The funding opportunities are of high importance for electrofuels, as they are still not commercialised. Moreover, parts of the production cycle, such as electrolysers and non-homogenous biomass gasification, can be further developed; therefore, the financial support for R&D needs to be established. Further demonstration of engine performances running on methanol or DME is needed, as there are indications that using these fuels shows efficiency improvements. The funds should be earmarked for electrofuels, including, among others, the following areas: electrolysers, biomass gasification, CO_2 capturing and recycling/utilisation, and methanol, DME or methane vehicles.

- **Create research and industrial networks for knowledge transfer**

  There are already some demonstration facilities for electrofuel production, but there is a need for a joint network between the industrial producers of technology and the researchers. Knowledge transfer and sharing of the experiences from the pilot and demonstration facilities are important to expand the market for these fuels.

EARLY DEPLOYMENT INITIATIVES

- **Legislation development that will support higher alcohol or ether blends**

  The barriers for using methanol or DME as transport fuel in the current legislation are related to the blends for alcohol and ether fuels, which are 3% and 22% respectively. Even with the blend restrictions in place, the blends are not obligatory, so they do not support the adding of these fuels to petrol. This would be a part of incremental planning with an aim to increase the blends, as it is technically shown that cars can run on 100% methanol and DME. The change in blend restrictions in the newer legislations will enable more presence of these fuels on the market, which would simultaneously create the market for vehicles and needed infrastructure.

- **Develop emission accounting for carbon capture and recycling**

  Developing emission accounting for carbon capture and recycling will enable the possibility of calculating the effects of emission-to-fuel production compared to other fuel production cycles. It will also open a possibility to account CCR as a CO_2 reduction mechanism, whereby entering in the ETS monitoring.

- **Establish special market conditions for helping the introduction of dedicated vehicles or alternation kits on the market**

  In order to introduce the new technology to the market, which will then be competing with already developed technology, it is important to create special market conditions such as specific production quotas that are offered with an agreed price, or create a market for the dedicated vehicles/alteration kits by influencing the buying behaviour of the customers.

- **Initial subsidies for vehicle alteration for companies**

Subsidies for engine conversion to methanol or DME could speed up the use of these fuels on the market after they reach appropriate distribution and filling capacities. The subsidies can be dedicated to companies that would like to convert their heavy-duty trucks to these fuels. The benefit of giving the subsidies to companies that are transporting different goods is that the driving corridors are known; therefore, the investments in filling infrastructure can be adjusted to the most traffic-intensive corridors. Similar subsidies can be allocated for companies that would like to transform their ferries to electrofuels.

LONG-TERM DEPLOYMENT ACTIONS

- **Plan for new demonstration plants**

The successful demonstration of pilot-scale electrofuel production facilities is essential to open the door for scaling-up and commercialisation. This can lead to improvements in process efficiency and the cost reduction of technologies and fuel production. Creating a plan for demonstration plants that can be deployed in Denmark needs to be made in agreement with municipalities and their strategies. When the demonstration plants have been proven to be viable, the next step would be to scale up the technology and create a plan for establishing and building commercial plants.

- **Long-term investment plan for deployment of necessary infrastructure changes**

A long-term plan of electrofuel deployment needs to be developed as the potential of these fuels is in future energy systems mostly after 2030. Therefore, it is necessary to create a plan that has transition steps that will pave the way for electrofuel deployment. In addition, the necessary infrastructural changes will take time and certain investments, which needs to be included in the regional and municipal plans for the transport sector.

- **Profile Denmark as an important actor within electrofuels**

As a country with strong wind and catalysis industries and R&D in electrolysis and biomass gasification, Denmark has a high potential for electrofuel production. Moreover, with a long history of creating flexible energy systems that can integrate a high share of renewables, the predisposition to integrate these fuels in the system is rather high. This should be used for the promotion of Denmark as an important actor within electrofuels. Demonstration facilities for electrofuels should be prioritised – not only for job creation opportunities, but also to meet the goal of a 100% renewable system. As it is already internationally recognised as a renewable energy developer, by pursuing the electrofuels as a transport solution, Denmark will confirm its green profile.

10 CONCLUSION AND FURTHER WORK

The conducted research indicates that electrofuels for heavy-duty transportation are a feasible element in energy systems and could play an important role in future energy systems with a high share of fluctuating renewable energy. The electrofuels provide a new concept of producing hydrocarbons by merging carbon with hydrogen produced by converting electricity through electrolysis. The cross-sector approach in the fuel production, by redirecting the excess electricity to the transport sector, is creating the flexibility and storage buffer for fluctuating electricity in the form of chemical energy. This overcomes the lost flexibility on the resource side by having fluctuating renewable resources by creating flexibility within the system. The feasibility of electrofuels was evaluated in the Danish 100% renewable energy scenario for 2050, through their capability of fluctuating resource integration, the competitiveness of fuel production costs with different biofuel alternatives, and socio-economic costs of these fuels as part of the energy system.

Reviewing the individual stages of the production cycle has indicated that there is a need for further development of key technologies: biomass gasification and high-temperature solid oxide electrolysis cells (SOEC). The development of the air carbon capture will eventually have to be prioritised if the aim is to completely eliminate biomass in the transport sector, and the carbon bottleneck from the stationary resources will not be able to meet the transport demand. Furthermore, on the infrastructure side, the demonstration of vehicle performances running on methanol and DME, with dedicated and alternated vehicles, is needed in order to further understand the efficiencies and potential issues of using these fuels. The analysis of electrofuels in the energy system showed an increase in the integration of renewable resources, which is a direct result of the production process based on the wind and electrolysers. This is of special importance in 100% renewable energy systems that need a balancing capacity that will enable an extensive penetration of fluctuating sources into the grid.

The electrofuel pathways were compared with electrification, hydrogen, first- and second-generation biodiesel, two bioethanol scenarios, and biogas as transport fuel alternatives. This was not done in all stages of the analysis, but every stage has included at least three alternatives. From an energy and resource perspective, the most efficient forms of transportation are direct electrification and hydrogen. While direct electrification should be used to the maximum extent possible, some modes of transport cannot be electrified. Hydrogen as a transport fuel has its advantages when produced from renewable sources; however, there are concerns about on-board storage for heavy-duty transportation, and the infrastructure costs are significantly higher than for other fuel types. As a solution that can be used for parts of the transport sector which cannot be electrified, electrofuels show a good balance of energy and resources use. The high production efficiencies for bioelectrofuels and CO_2 electrofuels of ~78%[15] and ~60%[16], respectively, are a very important factor for choosing these fuel production processes. Out of the two analysed fuel outputs, the production of methanol/DME is more efficient than methane, and associated costs for altering existing infrastructure are lower. When it comes to the fuel production costs, the only biofuel pathway that results in lower fuel production costs than all electrofuel pathways is first-generation biodiesel, while second-generation biofuels have higher production costs. Out of electrofuel pathways, bioelectrofuel is cheaper in the case of methanol/DME production, while in the case of CO_2 electrofuels, methane is cheaper. However, the sensitivity analysis showed that the results vary depending on the data used, especially data on vehicle efficiencies. If the technological development continues with the same trend as today, it seems more probable that liquid alternatives will be used instead of gaseous. However, this does not mean that there is no space for applications of gaseous fuels as part of the transport sector. The key concern in the short term should be the development of critical technologies that are in common for the electrofuel production cycle, and the final fuels can be adjusted when the factors on the demand side of the transport sector are clearer.

An implication of deploying electrofuels in the system is visible in the socio-economic costs, as the high investments in wind and electrolysers result in high system costs. Even though electrofuel pathways are investment-intensive, as they use less or no biomass resources for fuel production than biofuel alternatives, their overall costs are lower in some cases. The sensitivity analysis on different wind and electrolyser costs has shown that the influence on the total cost can be up to 15% in comparison with the reference year of 2050. Another sensitivity analysis indicates that even if the use of solid oxide electrolysers is not fully developed, already commercialised alkaline electrolysers can be used and, as a result, slightly higher investment costs will occur. The results for the fuel production costs showed that electrofuels are competitive with biofuels and with projected petrol prices in the future when associated CO_2 costs are accounted for. These findings suggest that electrofuels do have the potential to replace fossil fuels in the future. Ultimately, the cost calculations performed in this dissertation are based on the current predictions of development of technologies in the future, which is a weakness of the long-term calculations, especially in the case of technologies that are currently on an R&D level. However, this study managed to evaluate the potential of electrofuels in the future, and knowing that the infrastructure investments are cost-intensive and have a long-term effect on the system, it can be seen as a springboard for more detailed electrofuel analysis.

The historical development of alternative fuel policies has indicated that the choice awareness of alternative fuels, especially renewable alternatives, was eliminated by having

[15] Fuel output divided by biomass and electricity input
[16] Fuel output divided by electricity input for electrolysis and CO_2 recycling

biofuels as the main focus in the legislation in the last 15 years. The current legislation does not favour electrofuels, nor does it recognise them as renewable fuels in most of the cases. Moreover, the use of alcohol or ether fuels such as methanol and DME suggested in this study is restricted on the market to low blends. The present findings suggest several courses of action in order to help the deployment of electrofuels in the future, which has been reported as a roadmap for electrofuels. There is a need to modify the legislation in order to support recycling of carbon dioxide as a measure for climate mitigation and to enable high blends of alcohol and ether fuels. Furthermore, extensive funding should be put in place to support the research and development of critical technologies needed for fuel production; finally, there is a need to support demonstration facilities and, eventually, the scaling-up of the technology. The knowledge transfer from the established plants, such as the one in Iceland, and the new plant in Germany would help to further the development and get more actors involved. The benefit of having electrofuel technology researched and demonstrated within the EU borders should be used as an advantage; moreover, by enhancing the support for these fuels, the European Union can become a leading actor in establishing fuel security. More specifically, Denmark, as a Member State that already has many resources involved in the R&D of technologies needed for production, strong wind and catalysis industries, and, essentially, a developed energy system with high integration of renewable resources, should further encourage the demonstration of electrofuel production. Electrofuels offer a potential solution for transport which will help to reach the Danish goal of having a 100% renewable energy system in 2050. Finally, this research could be helpful in opening discussion among policymakers about new solutions for the future of the transport sector.

10.1 FURTHER WORK

In general, a deeper understanding of the potential problems of the production process, based on the experiences from the demonstration plants in place, could guide research to specific problem areas. The research carried out in this dissertation has investigated some aspects of the feasibility of electrofuels in future energy systems, and future work planned will focus on potential geographic distribution of production plants based on the resources available and the impacts of electrofuels on different types of energy systems.

Still, there are many opportunities for future research from third parties, such as:

- **Investigation of synergies of electrofuel conversion plants**

Detailed investigations on modelling the production cycle and different modes of plant operation could explore many synergies that can be achieved in the electrofuel production process. Surplus heat produced by chemical synthesis and oxygen from the electrolysis should be utilised in the process if possible. This will further enable exploring the possibility of different plant designs that can be used for either centralised or decentralised fuel production.

- **Improving electrolyser performances**

Furthermore, as the high-temperature SOECs are still under R&D, there is a need for increasing durability of the cells and to explore the performance with intermittency of the electricity from renewable sources. Experiments on this matter are important in order to confirm the assumptions that there will be no significant consequences of this type of operation on the electrolysers. The experimental data on reverse operation of SOECs in fuel cell mode is relevant to explore the opportunity to run the device in both the fuel and electricity production mode, the time frame for starting the operations in both modes, and potential consequences of this type of operation.

- **Drive-cycle analysis of heavy-duty vehicles running on electrofuels**

The wider knowledge on vehicle performance and conversion of vehicles with high blends or pure methanol or DME could guide the market towards one of those fuel choices. There are vehicles running on these fuels worldwide, but the data is not publicly available and it is difficult to obtain it from the sources that potentially have it. Further demonstration of the engine performances in Europe would be beneficial for improving the knowledge on these technologies, and transparent sharing of obtained data should follow the demonstration projects.

- **Analysis and development of electrofuels for aircrafts**

The upgrade of electrofuels to jet electrofuels should be further researched and performances of aircraft propulsion systems running on this fuel should be investigated. The final part of the pathways should be modified for production of jet electrofuels, as there is a need to use different fuel synthesis in order to produce kerosene, which is currently used as jet fuel. With the aim of maintaining as much of the present aviation infrastructure as possible, the effect of jet electrofuel on aircraft design should be further analysed.

- **Syngas transportation and storage characteristics**

The data on syngas transportation and costs is very difficult to obtain as it is not heavily investigated and reported in the literature. It is important that this knowledge gap be eliminated, with more research focusing on this specific gas mixture. It could be beneficial for the energy system that the transportation and storage be an option, as this can influence the design and locations of production facilities.

- **Assessing and documenting environmental impact of electrofuel production**

There are polemics on whether recycling of carbon emissions is helping the emission reductions or whether it is just transferring emissions from one sector to another.

Conducting analysis on environmental impacts of electrofuel production could shed light on the actual impact of emission reduction by, for example, producing CO_2 electrofuels. This is important in order to clarify the role of electrofuels in climate mitigation and to be able to classify the fuels as carbon-neutral. Moreover, it is important to investigate the environmental impact of materials and resources used in the production cycle, e.g. materials used for electrolyser modules or water use for hydrogen production.

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